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AUTHORITY
usaec ltr, 4 feb 1966

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FOR ERRATA

AD 437141

THE FOLLOWING PAGES ARE CHANGES

TO BASIC DOCUMENT

ERRATA SHEET

Eitel-McCullough Contract No. DA 36-039 SC-90818 - Research on Microwave Window Multipactor and its Inhibition (Sixth Quarterly Progress Report).

Reference is made to the Sixth Quarterly Progress Report on the above program recently mailed to you.

Section 8, ABSTRACT CARD. This section was inadvertently omitted in the printing and binding process.

The enclosed abstract cards should be inserted in this report so as to effect a ready reference and to complete your volume.

EITEL-McCULLOUGH, INC.
301 Industrial Way
San Carlos, California

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San Carlos, California

Microwave Window Multipactor and Its Inhibition by D. Preist

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Unclassified Report.

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1. Multipactor
2. Microwave Windows
3. Microwave Power Generation

I. Preist, Donald
II. Project Defender
III. USAELRDL Contract No. DA-36-039 SC-90818
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RESEARCH ON MICROWAVE WINDOW MULTIPACTOR AND ITS INHIBITION

REPORT NO. 6
CONTRACT NUMBER DA 36-039 SC-90818
DEPARTMENT OF THE ARMY
TASK NUMBER 7900.21.223.15.00

SIXTH QUARTERLY PROGRESS REPORT

1 OCTOBER 1963 THROUGH 31 DECEMBER 1963

U. S. ARMY ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORIES
FORT MONMOUTH, NEW JERSEY

EITEL-McCULLOUGH, INC.
301 INDUSTRIAL WAY
SAN CARLOS, CALIFORNIA

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SIXTH QUARTERLY PROGRESS REPORT
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Object of Research: (1) Attain a more complete theoretical understanding of microwave tube window multipactor, its inhibition and sustainment, and the tube performance limitations it imposes; (2) Investigate techniques to inhibit multipactor without degrading tube performance.

Prepared by: R. Hayes
Raymond Hayes

Approved by: D. Preist
Donald H. Preist

This research is a part of Project Defender, sponsored by the Advanced Research Projects Agency, Department of Defense, under ARPA Order Number 318-62, Project Code Number 7300, and is conducted under the technical guidance of the U. S. Army Electronics Research and Development Laboratories, Fort Monmouth, New Jersey.

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1. PURPOSE

This is the 6th report of a 2 year research program on multipactor at microwave windows. The broad purpose of the program is to provide a deeper understanding of multipactor effects at waveguide windows used with high power microwave tubes. Also to devise practical methods for preventing or eliminating multipactor, thereby raising the power handling capacity of windows.

The first year's work demonstrated clearly that various methods of reducing multipactor could be used with success. These included evaporated titanium coatings, sputtered titanium monoxide coatings and grooves on fused silica windows without coatings. All these methods have worked successfully on circular disc windows, at peak powers from 60 to 80 megawatts effective transmitted power and average powers up to 50 kilowatts at about 2850 megacycles. One of the main pruposes of the second year of work is to obtain more detailed knowledge of the behavior of these methods, especially the coatings, and to arrive at numerical values for the important properties involved. These include the useful range of thickness of the coatings, the conditions of application, the temperatures and other

factors involved in the processing and the constitution of the coating material itself.

Another major purpose is to test these windows at much higher average power levels than formerly. This is possible with the new test facility at Eitel-McCullough, Inc. Such high average power tests should reveal any weaknesses in the techniques used for multipactor suppression, and will approximate more closely than before the conditions existing in a super power microwave tube. An investigation of gas evolution from windows under multipactor conditions will be made to throw more light on the nature of the multipactor problem. Other phenomena such as window puncture and arcing which may cause power limitations will be investigated as the need arises. In addition, a reevaluation of other window geometries, such as cones and domes coated to prevent multipactor, will be made, as these offer significant potential advantages, compared with discs.

Summing up, the broad purpose of the work is still to provide a deeper understanding of multipactor effects and their inhibition, but in this second year the emphasis will be transferred from analysis of the phenomena

and pursuit of new methods of dealing with it to reduction to practice and complete engineering of techniques which so far have been demonstrated only on a laboratory scale.

2. ABSTRACT

Multipactor discharges at beryllia and alumina windows have been suppressed by both sputtered titanium suboxide coatings and evaporated titanium coatings. Tentative thickness limits in terms of sputtering current and time have been established for titanium monoxide coatings sputtered in argon. A range of coatings sputtered in mercury have been satisfactory but thickness limits have not yet been determined. Evaporated titanium coatings with resistivities at deposition in the region of 1 megohm/square have been the most satisfactory to date. Lighter coatings will suppress multipactor only after a period of operation. The upper limit of thickness has not yet been found.

Coatings have been tested at 2700/Mc/s up to equivalent transmitted powers of 40 Mw peak and 320 kW average without failure. Power has been limited by arcing at the metal-dielectric seal rather than by multipactor discharges.

The threshold power for arcing can be increased considerably by reducing the pulse width of the test facility from 20 to 3 microseconds. Other methods of increasing the peak power are discussed, including a new window design with increased arc resistance. Measurements of thickness versus resistivity of evaporated titanium films have been made.

3. PUBLICATIONS, LECTURES, REPORTS AND CONFERENCES

3.1 Conferences Held

There have been no conferences, lectures, reports or publications during this quarter.

4. FACTUAL DATA - PROGRESS TO DATE

4.1 Introduction

During this quarter sputtered titanium suboxide coatings on alumina and beryllia windows have been tested. Two types of sputtering equipment have been used to prepare the coatings, one employing an argon atmosphere and the other a mercury atmosphere. Both types of coatings have successfully eliminated multipactor when applied in sufficient quantity. Initially, difficulty was

experienced in maintaining a stable sputtering discharge but this difficulty has now been resolved by suitable modifications to the equipment.

Work on evaporated titanium coatings has been continued, with the emphasis on establishing upper and lower limits on the thickness of coatings suitable for the suppression of multipactor. It has proved difficult to define precise limits since the coating thickness is monitored indirectly and the resistivity of a coating varies considerably with subsequent processing of the window.

It was reported in the 5th Quarterly Report that many evaporated titanium coatings support weak multipactor discharges when first subjected to high rf power but that such discharges disappear after a period of operation. This clean-up process has been investigated further. It appears that the process occurs more readily with light coatings, some windows with thick coatings have been tested with a complete absence of discharges.

Since using the new high power test facility specially built for this program, it has not been possible to reach the peak power levels that were attained when testing windows in other facilities including the one previously used on this program. Possible reasons are the difference in pulse width and the fact that windows are now tested in brazed assemblies.

4.2 Titanium Monoxide Sputtering

The mercury diffusion pump bell jar system was installed early in the period and is operating satisfactorily. With liquid nitrogen in the cold trap the ultimate pressure is below 1×10^{-6} Torr indicating a leak-tight system and a high pumping speed. These factors should contribute to low contamination. When sputtering, no liquid nitrogen is used so that the mercury vapor from the pump provides the sputtering medium. In this case, the vacuum gauges indicate the pressure of the mercury with the residual gas supplying only small parts of the total pressure.

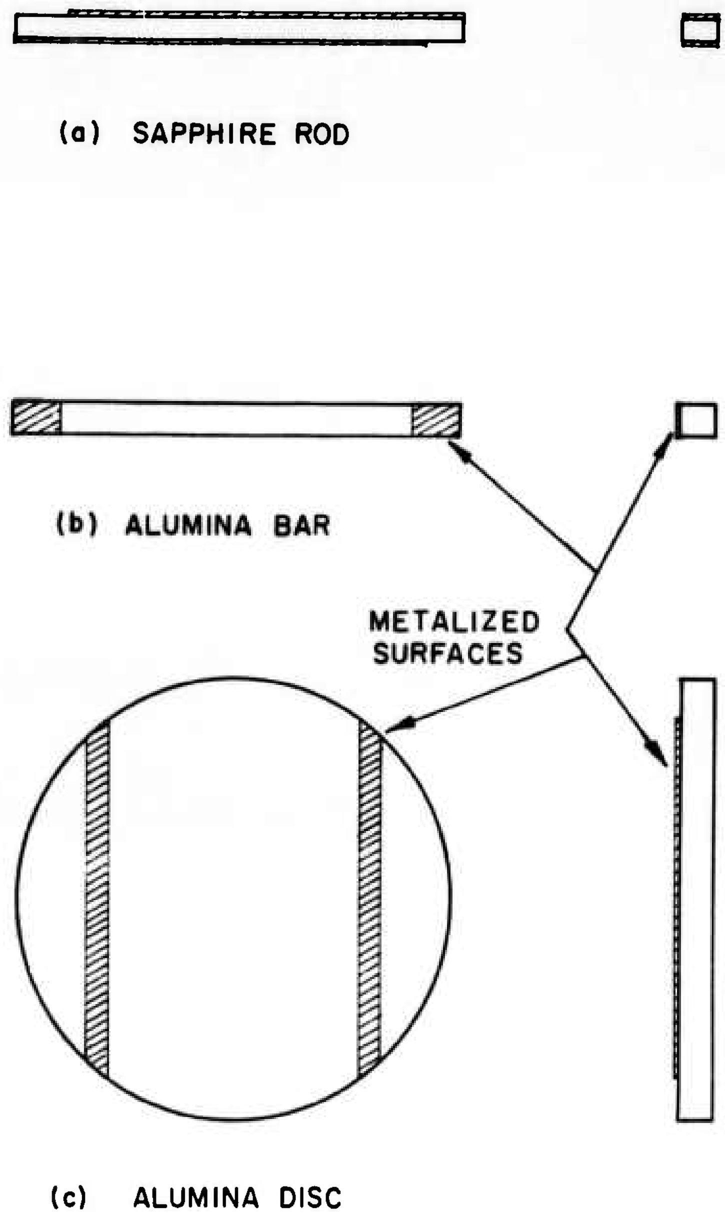
Initially, it proved very difficult to achieve significant sputtering currents using the mercury system even with the aid of the rf power for confining the plasma. This was traced to insufficient rf field strength in the gas plasma due to poor matching of the load to the rf generator. After this was improved, reasonable sputtering currents (over 2 mA.) could be obtained with a mercury vapour pressure low enough to provide a mean free path greater than the distance between the TiO target and the window. This is essential to prevent significant collisions between TiO molecules and molecules of background gas.

It has been found difficult to keep sputtering current constant over the period of time required (of the order of hours) and to maintain the same conditions for each coating operation. In the interest of speed and economy, more emphasis is now being placed on sputtering with argon. In contrast with the mercury system there has never been any problem getting high sputter currents in

argon, even with low rf power input. However, it was difficult to keep the sputtering constant over long periods because of gas pressure fluctuations. This situation has been remedied by changing the valves used to control the argon flow. The pressure and, therefore, the sputtering current can be held to any desired value for a long period of time with very little attention. This equipment appears to be satisfactory for coating control experiments and measurements.

4.3 Evaporated Titanium Coatings

At the beginning of the program evaporated titanium coatings with resistivities of the order 10^{10} ohms/square were used. To monitor such high resistivities a sapphire bar metallized on 2 faces as shown in Fig. 1(a) was employed. This provided a short resistance path with a large surface area so that when the unmetallized face was coated the actual resistance of the bar was about 100 times less than



VARIOUS TYPES OF MONITOR FOR THE MEASUREMENT OF COATING RESISTIVITY

Figure 1

the resistivity of the coating. Such resistance values were easily and reliably measured on a megohmeter.

Recently coatings having resistivities of the order of 1 megohm/square have been required. For these values the sapphire bar has not been satisfactory. In a calibration run, coatings evaporated simultaneously on to the sapphire bar and an alumina window disc with metallized strips Fig. 1(c) had markedly different resistivities. The reason for the difference is not clear, the fact that the short resistance path on the sapphire bar can become contaminated more easily is a possible explanation. Tests have shown that alumina bars metallized at the ends and the alumina disc with metallized strips are more reliable resistance monitors and these will be used in future work.

Thin films of titanium are very unstable, the properties changing considerably with the surrounding conditions. As a result it is not possible to define coating limits precisely. During deposition

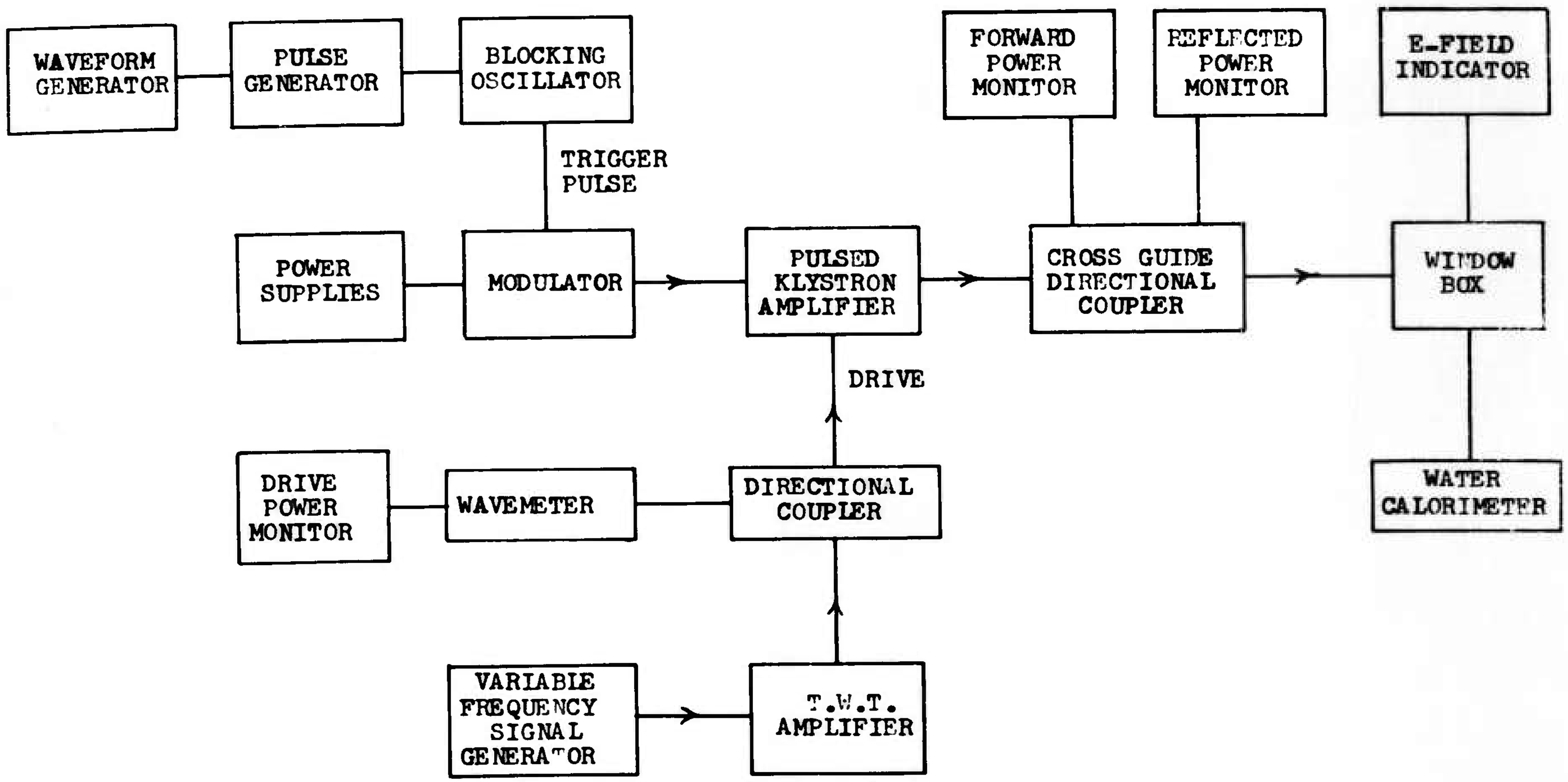
the resistivity of a film decreases as the layer builds up. When the evaporation process is stopped the resistivity gradually increases, presumably due to oxidation of the titanium and probably to some degree of contamination. If the substrate is exposed to the atmosphere the film resistivity increases by several orders of magnitude. On replacing the substrate in a good vacuum and heating at low pressure the resistivity of the film decreases again due to reduction but seldom reaches the original value.

Since coated microwave windows used in test units or in an actual tube must inevitably be subjected to different atmospheres during processing of the device, the final coating resistivity will vary considerably and may bear no direct relation to the original value measured during deposition. When using coated windows therefore it is important to consider all the processes to which the window is subjected in addition to the actual deposition.

Coatings for microwave windows are too thick when they start to increase the window losses appreciably. Since the shunt resistance of the test cavity is of the order of a few megohms, coatings with resistivities of this value would be expected to lower the cavity Q. Accordingly, window coatings have only been deposited down to resistivities of 2 megohms.

4.4 Procedure For Window Tests

As details of the high power test facility and the construction and processing of the window test units have been given in previous reports, only a brief description will be included here. A block diagram of the test facility and the arrangement used for window experiments is given in Fig. 2. Rf power is supplied by the klystron amplifier in the frequency range 2625 to 2775 Mc/s. A pulse width of 20 microseconds is used with a duty cycle variable up to 2% maximum. The klystron is driven by the signal from a variable frequency signal generator, amplified by a TWT amplifier. Power



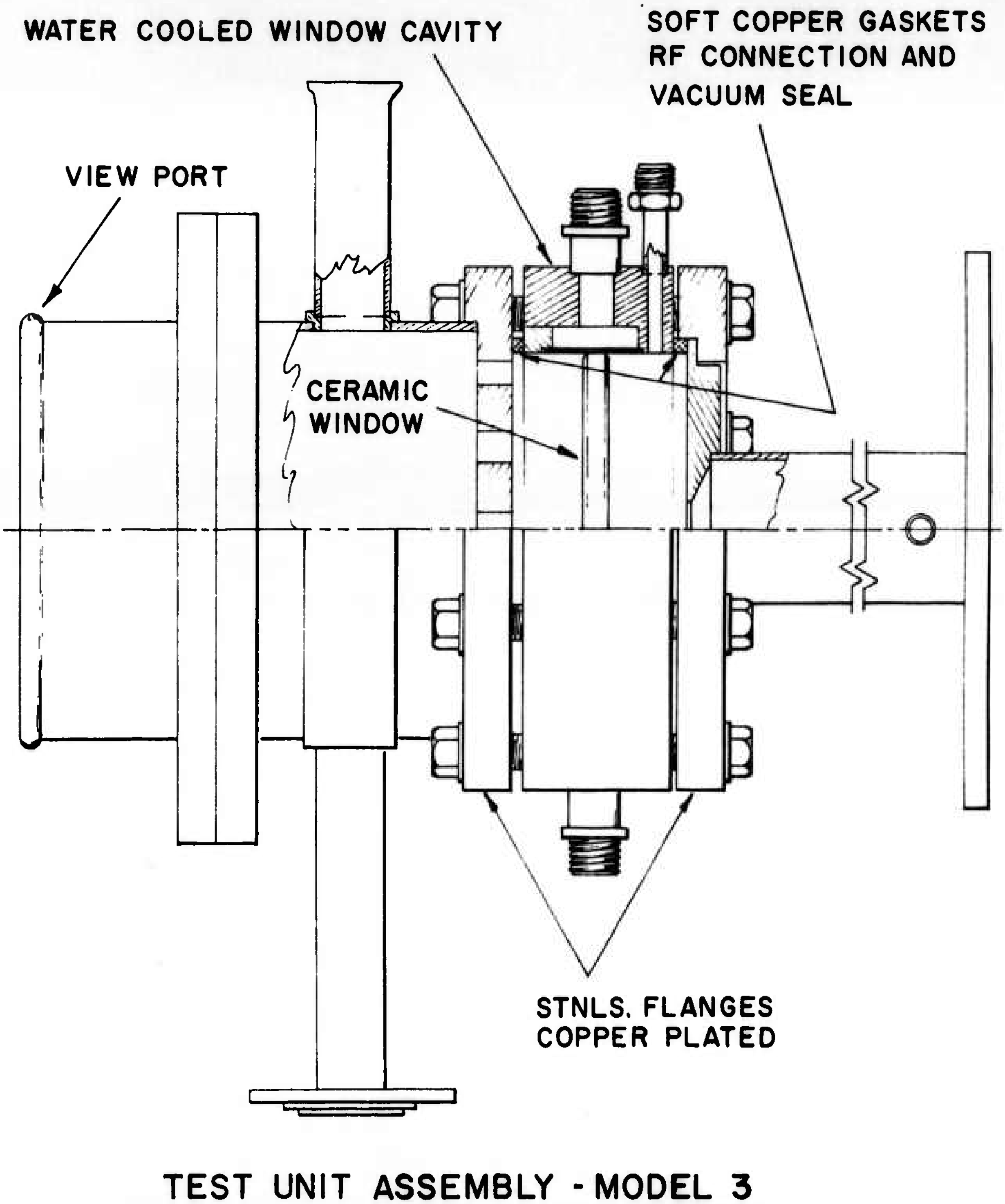
BLOCK DIAGRAM OF HIGH POWER TEST FACILITY

Figure 2

from the klystron is transferred to the window via a directional coupler which facilitates monitoring of the forward and backward power. The electric intensity within the cavity is measured by a probe connected to a bolometer.

Ceramic windows are metallized and brazed into an assembly which is used for the construction of test units as illustrated in Fig. 3. The window assembly forms a resonant cavity which has been designed to operate in the region of 2700 Mc/s. Assembled units are evacuated and baked to 400°C while on the pump, the final pressure at pinch off being less than 10^{-8} Torr. The test unit shown in Fig. 3 (Model C) is designed for evacuation on one side of the window only, a modified type (Model D) contains provision for evacuating both sides.

Prior to high power testing, the units are tested at low power to determine the resonant frequency, the input vswr at resonance, and the loaded Q of the unit. The Q is used to determine the ratio of the power dissipated in the cavity to the equivalent transmitted power.



TEST UNIT ASSEMBLY - MODEL 3

Figure 3

4.5 Tests on Sputtered Coatings

Test Unit 21, Coors BD96 Beryllia, Sputter-coated Q_L = 1300

The window tested in this unit was coated by sputtering titanium monoxide in an argon atmosphere at a pressure of about 1 micron. A sputtering current of 10mA at 1300 volts was drawn for 30 minutes, the rate was then reduced to 5mA at 1300 volts and sputtering continued for a further 30 minutes. During high power testing the window behaved satisfactorily. No multipactor discharges were observed throughout the test. The pressure inside the evacuated portion of the test unit remained at 1.10^{-8} Torr apart from a momentary increase to 2.10^{-8} Torr which occurred at a power level of 36 kw peak dissipation, 16 MW equivalent transmitted power (E.T.P.). This small pressure increase, probably due to surface outgassing, was rapidly pumped down by the getter ion pump attached to the unit. Thus, during the operation of this unit, there was virtually no "clean-up" period

observed such as that obtained with the windows tested previously and described in the 5th Quarterly Report.

The window was tested at various peak power levels up to 50 kw (22 Mw E.T.P.), the limit being set by arcing at the metal-dielectric seal. The maximum average power dissipated in the window as measured by the water calorimeter was 570 watts (245 KW E.T.P.). Fig. 4 shows a plot of the peak power dissipated against the square of the electric intensity within the cavity, the latter being scaled to give the approximate equivalent transmitted power. The linear relationship indicates the absence of multipactor.

Test Unit 24, Coors BD96 Beryllia $Q_L = 1000$

This window was coated by sputtering titanium monoxide in an argon atmosphere at a pressure of about 1 micron. The sputtering operation lasted 60 minutes at a rate of 4mA, 1300 volts. Thus the coating was thinner than that used in Test Unit 22, described previously.

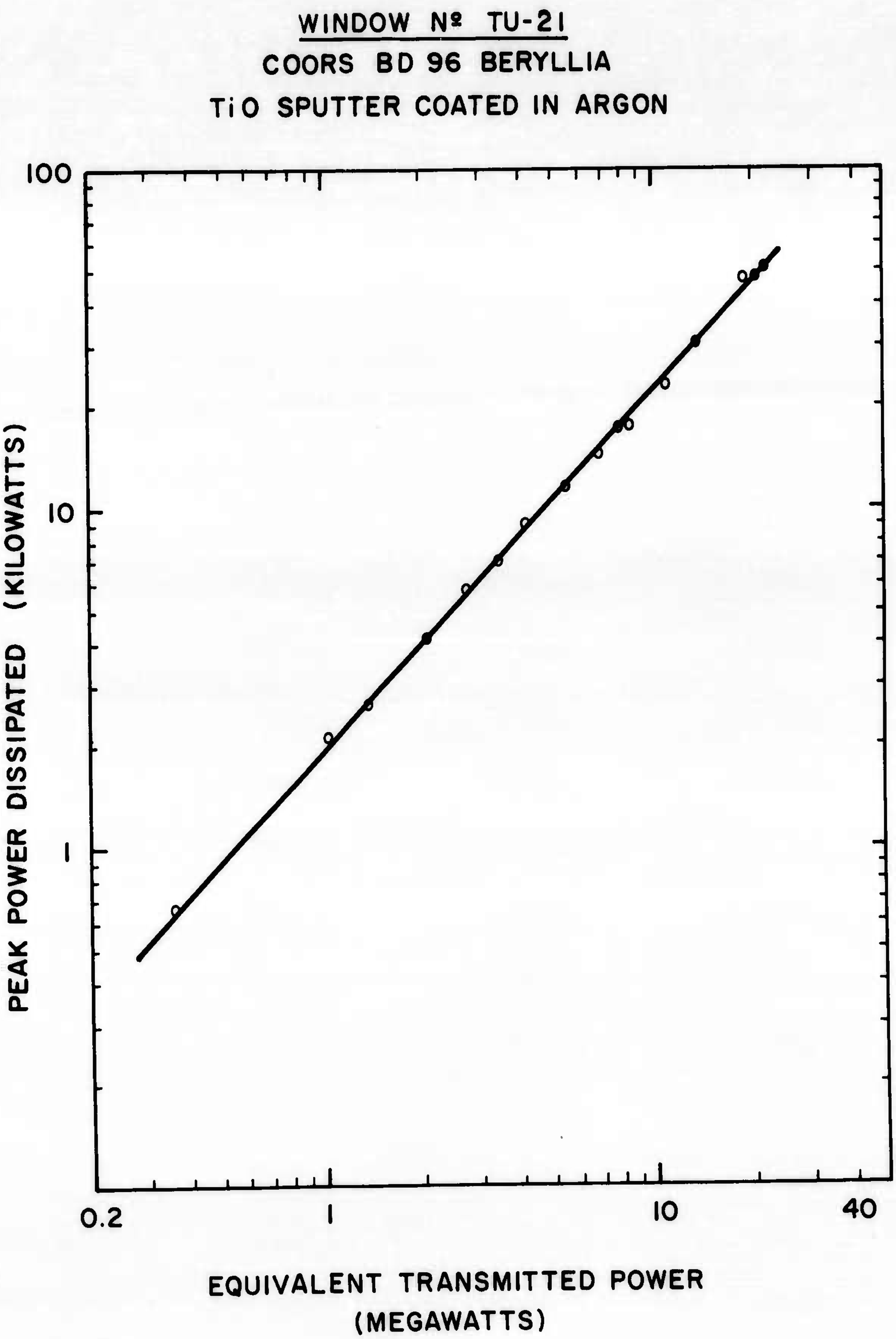

WINDOW Nº TU-21
COORS BD 96 BERYLLIA
TiO SPUTTER COATED IN ARGON
100
10
1
PEAK POWER DISSIPATED (KILOWATTS)
0.2
1
10
40
EQUIVALENT TRANSMITTED POWER
(MEGAWATTS)

Figure 4

Severe multipactor discharges were observed during high power operation of this unit. Discharges commenced at a peak power dissipation of about 1 KW (0.33 Mw E.T.P.) and continued at all powers above this level. Bright discharge glows were observed through the viewing window, having the characteristic pattern of the TE_{111} mode. The pressure indicated by the getter ion pump increased from 10^{-8} Torr and remained in the region 10^{-7} to 10^{-6} Torr during the discharge. There was no sign of the discharge diminishing through clean-up, although the unit was operated at high peak powers for a period of 2-1/2 hours.

A plot of peak power dissipated against cavity field strength squared is shown in Fig. 5. The nonlinear behavior due to power being absorbed by the multipactor is clearly indicated. Dissipation powers up to 100 kw peak were possible, as the reduced electric intensity within the cavity did not reach the threshold value for

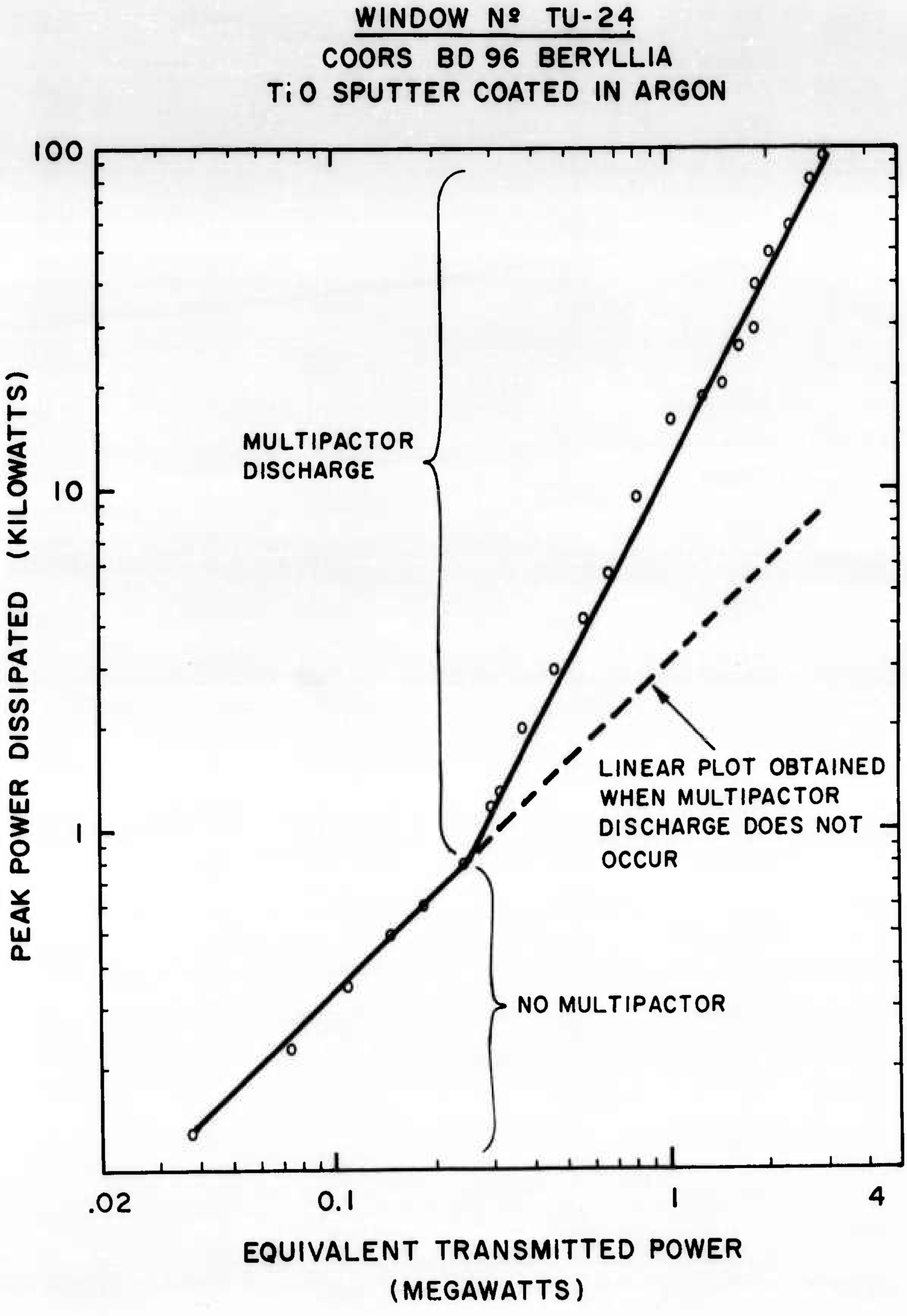

WINDOW Nº TU-24
COORS BD 96 BERYLLIA
TiO SPUTTER COATED IN ARGON
100
10
1
PEAK POWER DISSIPATED (KILOWATTS)
MULTIPACTOR
DISCHARGE
LINEAR PLOT OBTAINED
WHEN MULTIPACTOR
DISCHARGE DOES NOT
OCCUR
NO MULTIPACTOR
.02
0.1
1
4
EQUIVALENT TRANSMITTED POWER
(MEGAWATTS)

Figure 5

sparking. The power which could be fed into the cavity was limited by the mismatch between the cavity and the input waveguide which resulted from the multipactor.

<u>Test Unit 28, Coors BD96 Beryllia, Sputter-coated</u> $Q_L = 480$

As the coating tested in Test Unit 24 appeared to be too thin to suppress multipactor, thicker coatings were tried.

This window was coated by sputtering titanium monoxide in argon drawing a current of 15mA for 30 minutes followed by 6mA for 15 minutes at 1300 volts. When assembled in the test unit a loaded Q of 480 was measured. This low Q indicated that the coating was too thick and had introduced considerable loss into the cavity. Since this value is too low to enable high field strengths to be obtained in the cavity the unit was not tested at high power.

Test Unit 26, WESGO AL995 Alumina, Sputter-coated $Q_L = 500$

This was the first alumina window to be tested with a sputtered coating. The window was coated by sputtering titanium monoxide in argon for 60 minutes, drawing a current of 8mA at 1300 volts.

During alignment of the test unit at low power a loaded Q of 500 was measured. This low value indicated that the coating was too thick as in the case of test unit 28. It was decided to proceed with a high-power test although it was not possible to reach high field strengths (and hence high values of equivalent transmitted power) in view of the low Q. A certain amount of cleanup was observed during high power testing. At various power levels above 19 kw peak dissipation occasional sudden increases in pressure occurred. Such increases disappeared after a few minutes operation. The pressure increases did not appear to be associated with multipactor as no discharges were observed throughout the test. Clean up could be

attributed to outgassing of the cavity interior, but the degree of outgassing was much greater than that normally obtained with such units. The reasons for this were traced to two factors:

(1) During processing the unit was baked out to a temperature of only 200°C instead of the usual 400°C.

(2) During the test a blockage was discovered in the cooling water supply to the test unit which had become quite hot.

When the flow of cooling water had been restored no further pressure increases were observed during operation at power levels up to 67 kw peak. An increase in pressure from 10^{-8} to 10^{-7} Torr was observed when a magnetic field was applied perpendicular to the cavity axis and the line of maximum electric intensity. The pressure decreased to 10^{-8} Torr after 15 minutes operation; no discharge glow was observed during this period.

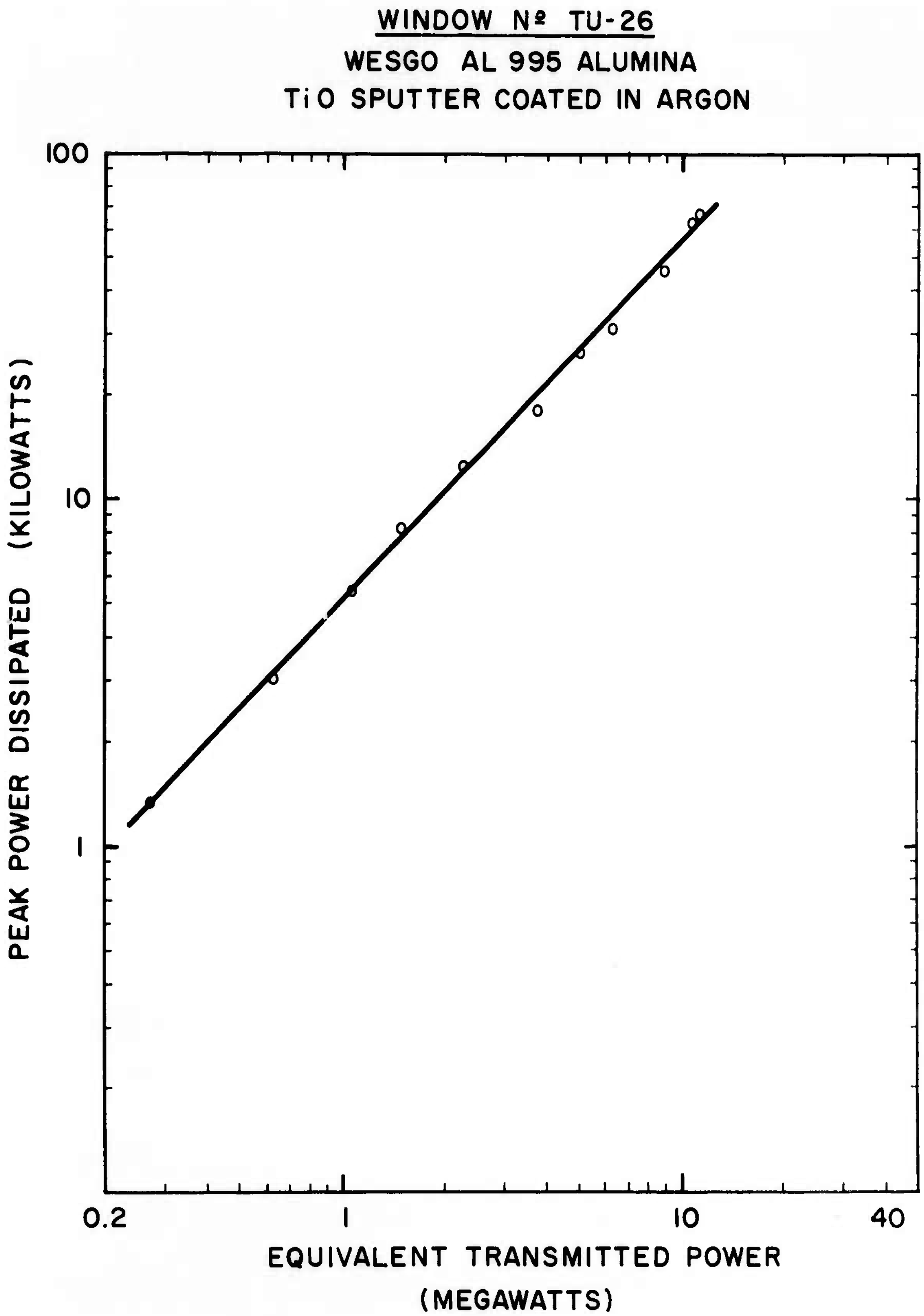

WINDOW Nº TU-26
WESGO AL 995 ALUMINA
TiO SPUTTER COATED IN ARGON
100
10
1
PEAK POWER DISSIPATED (KILOWATTS)
0.2
1
10
40
EQUIVALENT TRANSMITTED POWER
(MEGAWATTS)

Figure 6

Test Unit 23, Coors BD96 Beryllia, Sputter-coated in Mercury $Q_L = 1200$

The coating tested in this unit was applied by sputtering titanium monoxide in a mercury atmosphere at a pressure of about 1 micron. A current of 1.5mA at 1300 volts was drawn for 90 minutes. After cold testing, the unit was tested at high power, first to determine the maximum peak power possible at low duty cycle, and then to determine the behavior of the window when operating at high average power. Throughout this test no multipactor discharge was observed and the pressure in the evacuated portion of the unit remained at less than 10^{-8} Torr. The maximum peak power was limited to 42 kw peak dissipation (17 Mw E.T.P.) by arcing at the metal-dielectric seal. Average powers up to 510 watts dissipation (200 kw E.T.P.) were measured by the water calorimeter. The window was operated at this power for 1 hour with no signs of a discharge developing. A plot of

power dissipated against field strength squared was linear as shown in Fig. 7.

At the conclusion of the above test a crossed magnetic field was applied to the unit when operating at a power of 15 kw peak 300 watts average dissipation (6 Mw peak 1.2 kW average E.T.P.) to determine if multipactor could be induced by the field. The magnetic field was gradually increased, and at a value of 330 gauss a sudden pressure increase to 10^{-7} Torr was observed together with a faint but steady multipactor glow. After a period of operation the pressure decreased and the glow dissappeared. On increasing the magnetic field to 660 gauss the multipactor discharge was again obtained but cleaned up after a period of operation. The discharges obtained with the magnetic field were quite weak and did not affect the field strength in the cavity significantly. The magnetic field

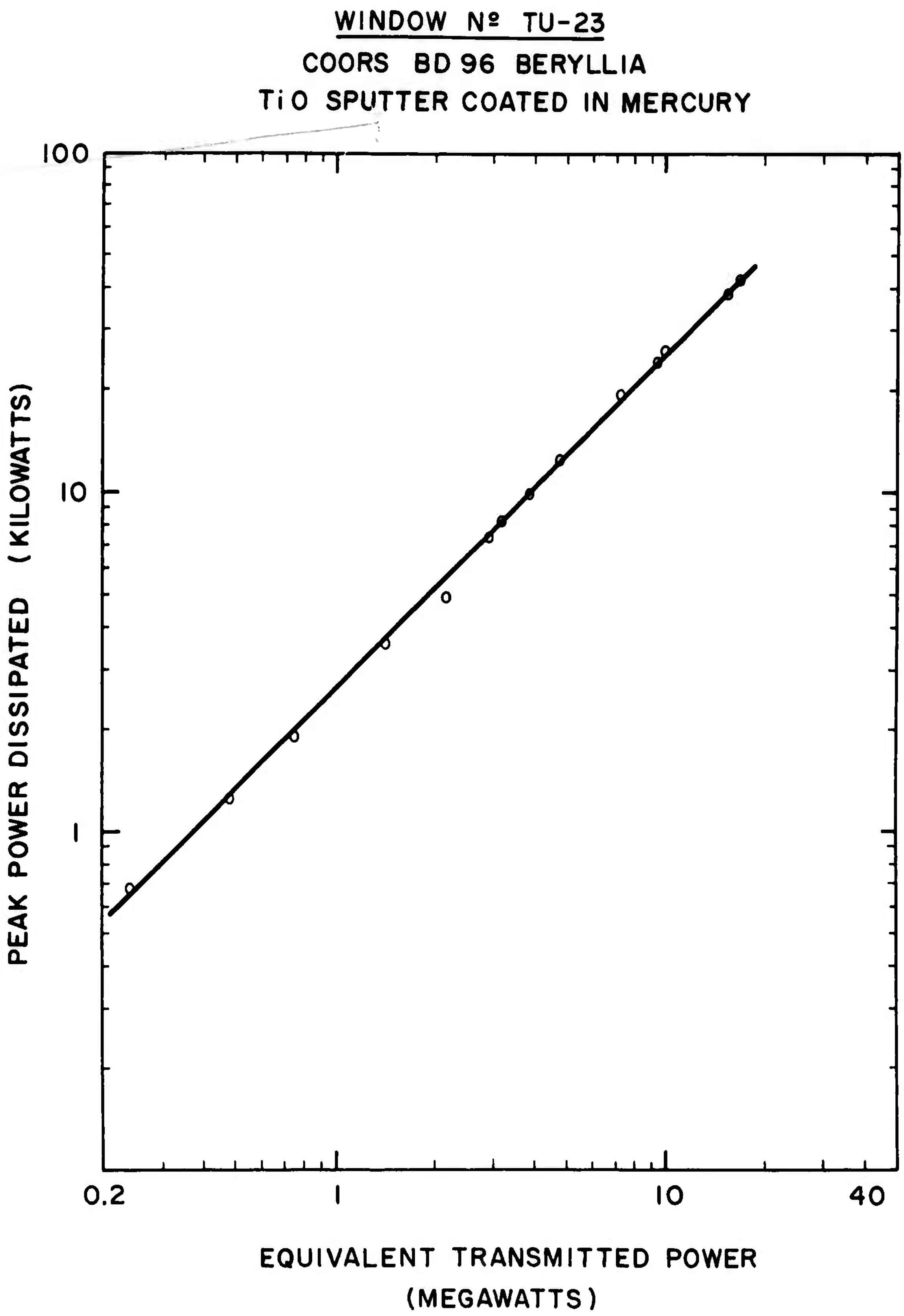

WINDOW Nº TU-23
COORS BD 96 BERYLLIA
TiO SPUTTER COATED IN MERCURY
100
10
1
PEAK POWER DISSIPATED (KILOWATTS)
0.2
1
10
40
EQUIVALENT TRANSMITTED POWER
(MEGAWATTS)

Figure 7

had the greatest effect at strengths of about 330 and 660 gauss, which correspond to approximately 1/3 and 2/3 of the magnetic field required for cyclotron resonance at the operating frequency (2700 Mc/s). At intermediate and higher values the multipactor discharge extinguished. The glow patterns were characteristic of those obtained with an external magnetic field. These have been fully described in the 4th Quarterly Progress Report.

<u>Test Unit 25, Coors BD96 Beryllia, Sputter-coated</u> $Q_L = 1300$

This coating was a little thicker than that tested in Test Unit 23. It was applied by sputtering titanium monoxide in a mercury atmosphere, drawing a current of 4mA at 1300 volts for 70 minutes. The unit was first tested at low duty cycles at powers up to 50 kw peak (22 Mw E.T.P.), the limit set by arcing. No glow discharges were observed and the pressure within the unit remained below 10^{-8} Torr. A plot of power dissipated against

the square of the field strength in the cavity was linear as shown in Fig. 8. When testing at high average power momentary increases in pressure were observed. At an average power of 535 watts dissipation (230 kW E.T.P.) the pressure was steady at 2.10^{-8} Torr but decreased after a period of operation.

The application of a crossed magnetic field produced an increase in pressure, the maximum effect occurring at field strengths of 330 and 800 gauss. This behavior is similar to that observed with Test Unit 23. The pressure gradually decreased during a period of operation with the magnetic field. No visible discharges were observed throughout the tests on this unit.

<u>Test Unit 33 WESGO AL995 Alumina, Sputter-coated in Mercury</u> $Q_L = 1350$

This window was coated by sputtering titanium monoxide in mercury, drawing a current at 1 mA at 1300 volts for 5 hours.

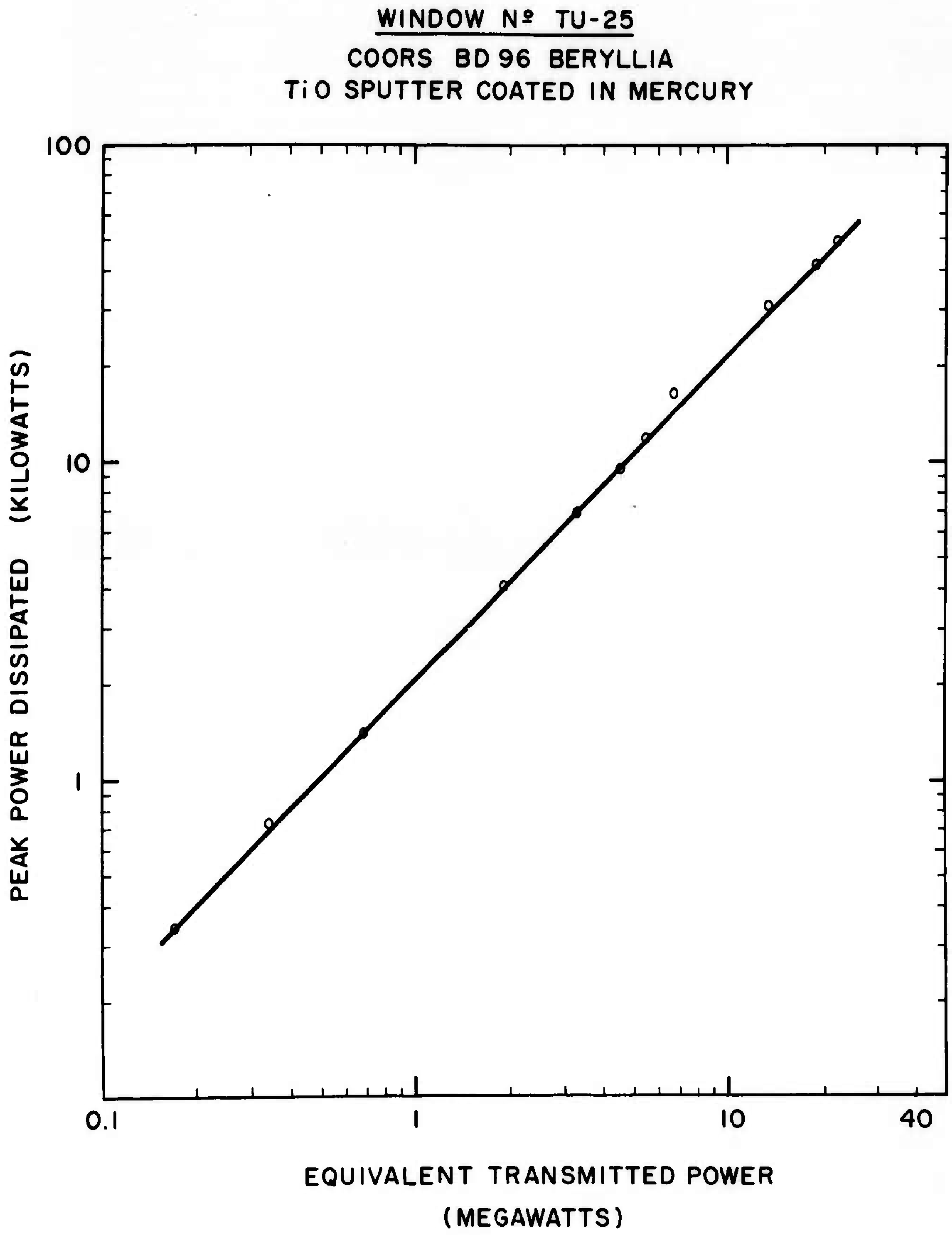

WINDOW Nº TU-25
COORS BD 96 BERYLLIA
TiO SPUTTER COATED IN MERCURY
100
10
1
PEAK POWER DISSIPATED (KILOWATTS)
0.1
1
10
40
EQUIVALENT TRANSMITTED POWER
(MEGAWATTS)

Figure 8

Intermittent multipactor occurred during initial operation of the unit but this cleaned up after a period of operation at a low duty cycle. A linear relationship between power dissipated and the square of the cavity field strength was obtained as shown in Fig. 9.

The threshold power for arcing in this unit was much higher than usual. Peak powers up to 94 kw dissipation (42 MW E.T.P.) were possible before arcing occurred. Since a standard window assembly was used, the reason for this marked increase in peak power capability is not clear. The most likely reason is an above average metal-ceramic seal. It was noticed that the brazed joint in this assembly was particularly good, there was little excess braze material and the finish was smooth. This would tend to minimize local field concentrations which give rise to arcing at low power levels.

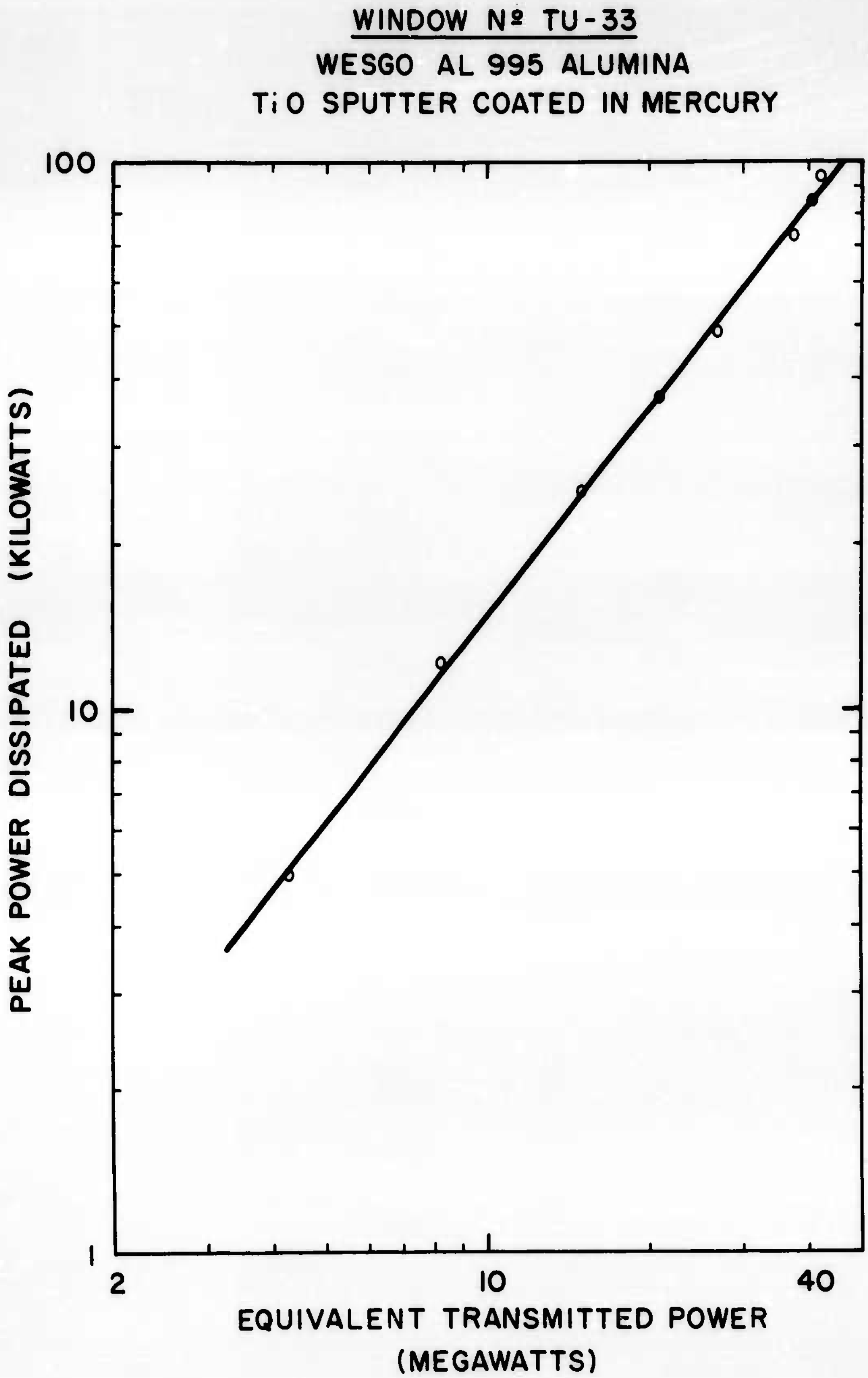

WINDOW Nº TU-33
WESGO AL 995 ALUMINA
TiO SPUTTER COATED IN MERCURY
100
10
1
PEAK POWER DISSIPATED (KILOWATTS)
2
10
40
EQUIVALENT TRANSMITTED POWER
(MEGAWATTS)

Figure 9

Operation at higher average power with a crossed magnetic field produced further multipactor discharges. The unit was operated at 150 watts average (68 kw E.T.P.) for about 1 hour before these discharges disappeared.

4.6 Tests on Evaporated Coatings

Test Unit 20, Coors BD96 Beryllia Evaporated Titanium coating $Q_L = 1030$

This unit was evacuated on both sides of the window to determine if higher peak powers could be sustained in vacuum without arcing. Normally, only one side of the unit is evacuated, the other side being pressurized to 15 lbs./sq. inch with SF_6 gas. The window was coated on both sides by evaporating titanium in vacuum to a coating resistivity of about 10^7 ohms/square*, monitored during deposition.

Intermittent multipactor occurred during the initial operation of the unit at high power, and a

* Actual value higher due to error in measurement.

considerable period of operation (about 1-1/2 hours), was necessary before cleanup of the window surfaces was completed. The discharges could be intensified by certain values of a crossed magnetic field, as described previously, and the field was used to shorten the clean-up period. A discharge obtained at a particular power level and magnetic field strength would gradually clean up, but often could be made to appear again by increasing the power level or altering the magnetic field strength. A typical situation is as follows:

Power dissipated 6 kw peak, magnetic field 330 gauss.

Time 0	Pressure	2.10^{-6}Torr	Steady glow
5 min.		2.10^{-6}Torr	Intermittent glow
10 min.		5.10^{-7}Torr	Glow steady but weaker
15 min.		2.10^{-7}Torr	Very weak glow

Power dissipated increased to 9 kw peak, magnetic field constant, pressure 2.10^{-6} Torr, steady glow.

In another situation the power dissipated was held constant at 18 kw peak and the magnetic field varied.

Magnetic Field	Pressure	
0	10^{-6} Torr	Weak glow
110 gauss	10^{-6} Torr	Brighter glow
220 gauss	10^{-7} Torr	No visible discharge
600 gauss	10^{-6} Torr	Steady glow
660 gauss	$5 \cdot 10^{-6}$ Torr	Distorted glow pattern

It is clear that for a strong multipactor discharge the combination of the microwave fields and crossed magnetic field in the cavity is quite critical. This behavior has been described in previous quarterly reports.

After a period of operation the multipactor disappeared and no further discharges were observed. The unit was then tested at dissipated powers up to 64 kw peak and 350 watts average. At this level arcing occurred at the seal. Due to the fact that the cavity loaded Q was somewhat lower

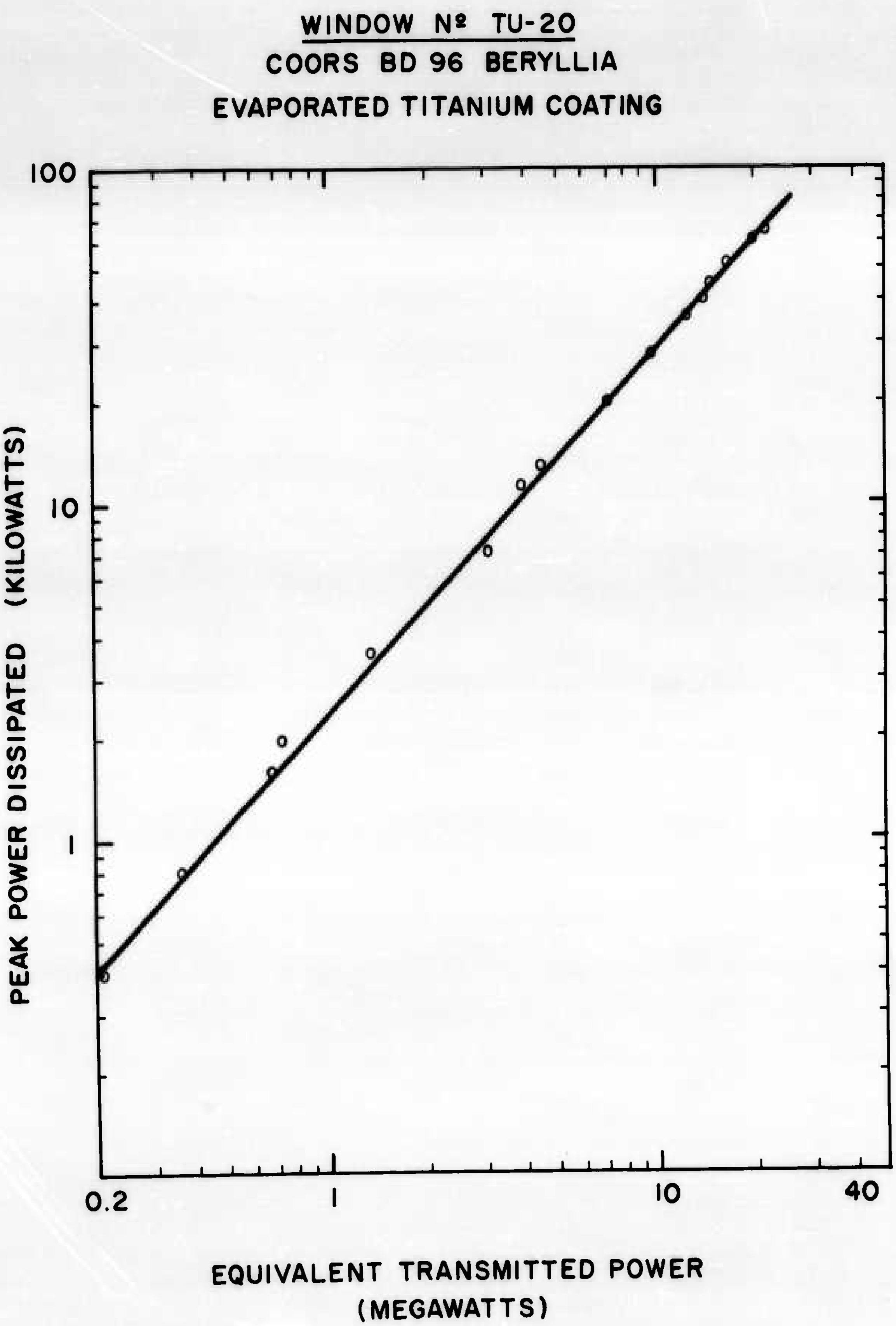

WINDOW Nº TU-20
COORS BD 96 BERYLLIA
EVAPORATED TITANIUM COATING
100
10
1
PEAK POWER DISSIPATED (KILOWATTS)
0.2
1
10
40
EQUIVALENT TRANSMITTED POWER
(MEGAWATTS)

Figure 10

than normal, the equivalent transmitted powers were only 22 Mw peak and 120 kW average. The maximum peak power is not significantly different to that obtained in units pressurized with SF_6 gas. This result confirms the tentative conclusion to the effect made on tests reported in the previous quarter.

<u>Test Unit 22, WESGO AL995 Alumina, Evaporated Titanium-coating</u> $Q_L = 1500$

In this window assembly the cylindrical walls of the cavity were coated, in addition to the ceramic, to determine if this procedure would eliminate the necessity for clean up during the initial operation of the unit. The ceramic was coated to a resistivity of about 10^7 ohms per square* (the same value used in T.U. 20) and the metal walls were coated until a visible film was obtained.

---

* Actual value higher due to error in measurement.

The additional coating on the metal walls did not prevent multipactor occurring when the unit was tested at high power. A considerable period of operation was required before the surface coatings changed sufficiently to prevent further multipactor. Clean up followed the same procedure as that described for T.U. 20. After this was complete, the power was increased to 45 kw peak dissipation (22 Mw E.T.P.), the limit set by arcing at the metal-dielectric seal.

While testing at high average power, two bright spots about 2 mm in diameter were observed near the center of the ceramic. These first appeared at a dissipated power of 150 watts average, (75kW average E.T.P.), glowing steadily and increasing in brightness as the power was increased to 230 watts average (115 kW E.T.P.). The unit was operated for 2 hours in this condition without

failure or deterioration. After the test the unit was dismantled and the ceramic surface inspected to determine if any pitting had occurred, but no signs of surface damage were found.

<u>Test Unit 29, Coors BD96 Beryllia, Evaporated Titanium-coating</u> $Q_L = 1300$

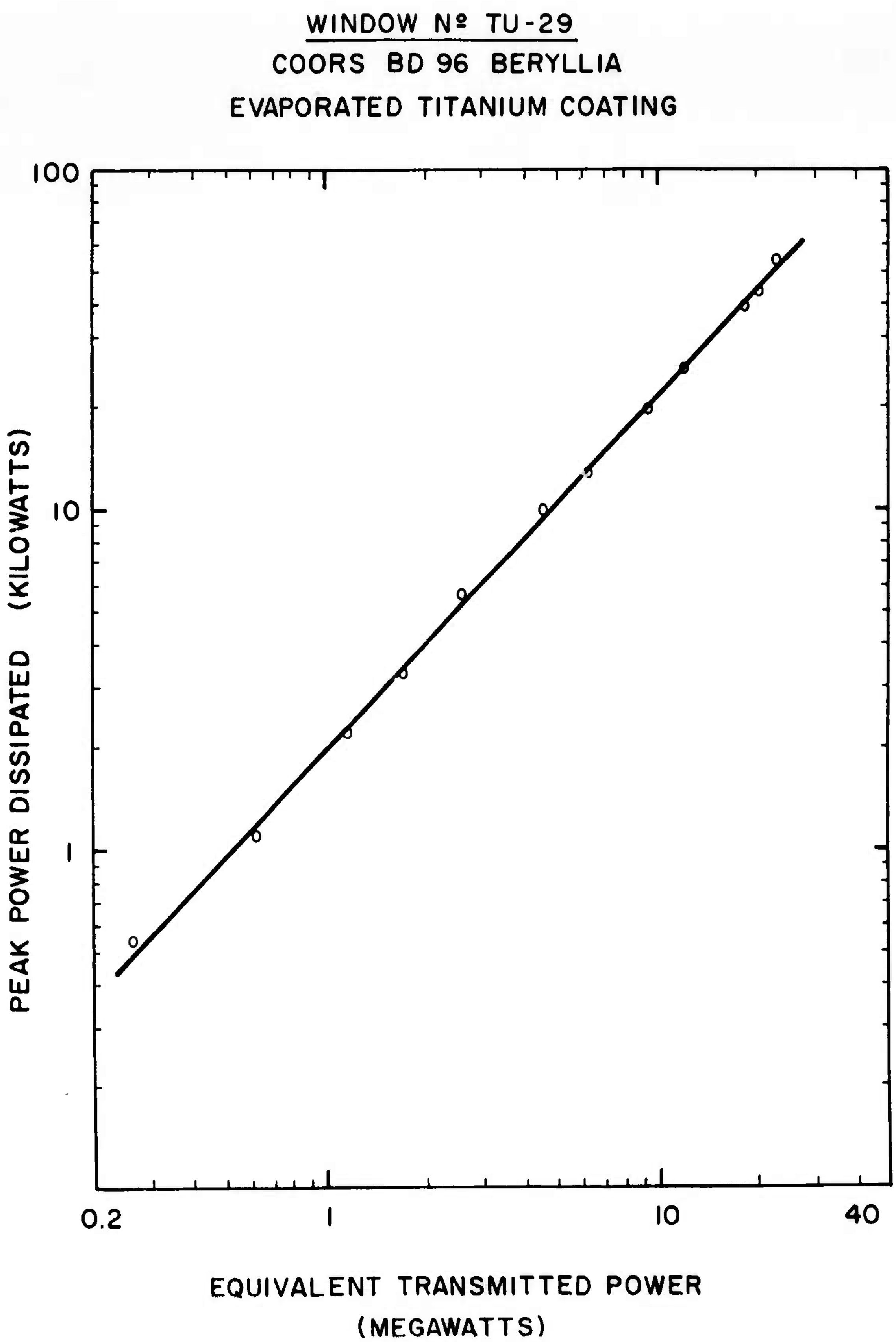
This window was coated to a resistivity of 2 megohms/square, a somewhat thicker coating than those previously tested. The modified system was used for monitoring the resistivity, giving better control of coating thickness and more accurate measurements.

The window performance during high power testing was good. No multipactor discharges were observed throughout the test and the pressure remained below 10^{-8} Torr during operation at high peak powers and a low duty cycle. At high average powers, the pressure gradually increased to 10^{-7} Torr, but there were no

sudden pressure increases that are characteristic of multipactor discharges. Peak power dissipation up to 55 kW (24 Mw E.T.P.) were obtained. The maximum average power was 750 watts (320 kW E.T.P.). This is considerably higher than normal, and was achieved through the use of additional water cooling adjacent to the cavity end plates. Despite the extra cooling, the unit became quite hot, which probably accounts for the pressure rise mentioned above. Test results on the window are given in Fig. 11.

Test Unit 31, Coors BD96 Beryllia, Evaporated Titanium-coating $Q_L = 1300$

To determine the effect of a hydrogen atmosphere at typical brazing temperature on evaporated titanium coatings, the window from TU 29 was heated to 750°C in dry hydrogen. The window was then assembled in this test unit and the assembly processed in the usual way.



WINDOW Nº TU-29
COORS BD 96 BERYLLIA
EVAPORATED TITANIUM COATING
100
10
1
PEAK POWER DISSIPATED (KILOWATTS)
0.2
1
10
40
EQUIVALENT TRANSMITTED POWER
(MEGAWATTS)

Figure 11

When tested at high power, the unit behaved in a similar manner to TU 29. No discharges were obtained and the pressure remained below 10^{-8} Torr throughout most of the test, increasing gradually to 5.10^{-8} Torr during operation at high average power. A linear plot of power dissipated against cavity field strength squared was obtained and is given in Fig. 12. The unit was tested at dissipated powers up to 52 kw peak (22 Mw E.T.P.) and 650 watts average (280 kW E.T.P.).

The maximum peak power dissipated in this and previous units was limited by arcing at the dielectric seal. If the rectified rf pulse is viewed on an oscilloscope, arcing is observed to shorten the pulse. At the sparking threshold, the last 1 or 2 microseconds are chopped off the normal 20 microsecond pulse. On increasing the input power, a greater portion of the pulse is chopped off, but a considerable

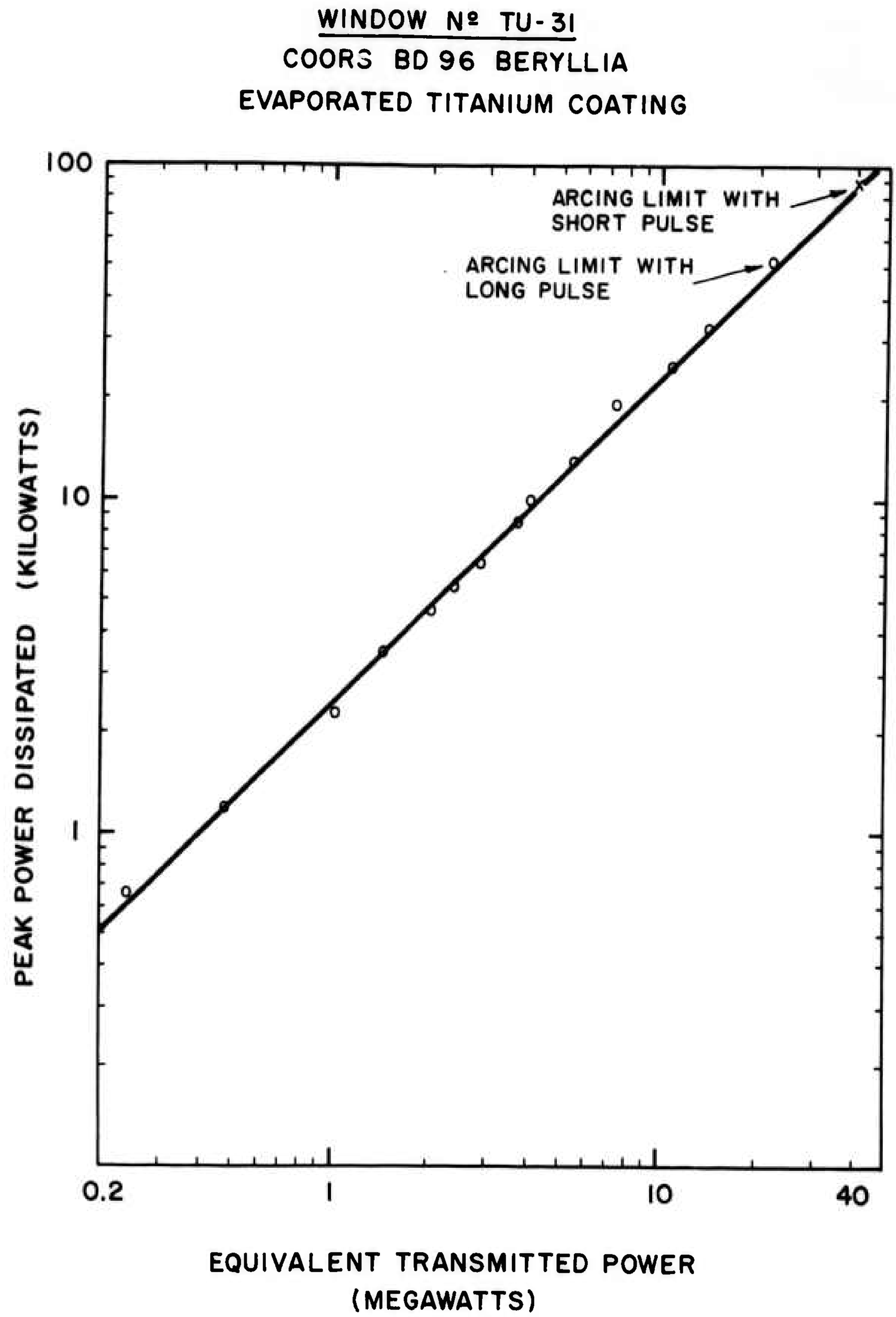
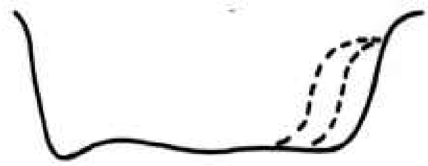
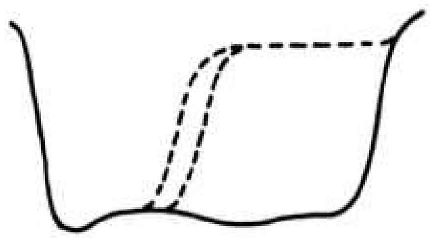

WINDOW № TU-31
COORS BD 96 BERYLLIA
EVAPORATED TITANIUM COATING
ARCING LIMIT WITH SHORT PULSE
ARCING LIMIT WITH LONG PULSE
100
10
1
PEAK POWER DISSIPATED (KILOWATTS)
0.2
1
10
40
EQUIVALENT TRANSMITTED POWER (MEGAWATTS)

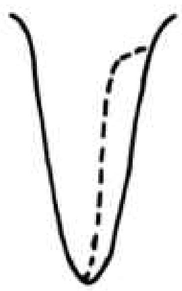
Figure 12



(a) 20 μs PULSE, ARCING THRESHOLD



(b) 20 μs PULSE, PEAK POWER INCREASED 50 %



(c) 3 μs PULSE, ARCING THRESHOLD

DISTORTION OF RECTIFIED R.F. PULSE DUE TO ARCING

Figure 13

increase in power is required to reduce the complete pulse. It seemed possible that with shorter pulse widths higher peak powers would be obtained. Accordingly, the modulator delay line was modified in a temporary manner to provide a pulse of about 3 microseconds duration.

On testing the unit with this short pulse, considerably higher peak powers could be realized. Since the short pulse was of irregular shape, only approximate power values were obtained but it appeared that the peak power could be increased by almost 100%. A maximum peak power dissipation of about 90 kw was achieved, which corresponds to a transmitted power of 40 Mw.

Test Unit 32, WESGO AL995 Alumina, Evaporated Titanium-coating $Q_L \approx 1500$

This window was coated to a resistivity of 20 megohms using the modified monitoring system. The test unit in which the window was originally assembled developed a leak just before testing and had to be rebuilt; the window was consequently baked and processed twice.

A few traces of multipactor were observed during initial testing of the unit, but these rapidly disappeared after a short period of operation. Through the remainder of the test no discharges were obtained and the pressure remained below 10^{-8} Torr. Fig. 14 shows a linear relation between power dissipated and cavity field strength squared. Multipactor could not be induced by a crossed magnetic field applied, at various strengths up to 1200 gauss, at a number of different power levels.

With this unit, the arcing level occurred at a power dissipation of 31 kw peak (15 Mw E.T.P.), a value somewhat lower than normal. In an attempt to increase the arcing limit, the modulator delay line was again modified for operation with a short pulse and the unit retested in this condition.

The rectified rf pulse shape was carefully noted and an accurate value for the duty cycle determined. The power values obtained with the short pulse are denoted by crossed in Fig. 14. The maximum peak power obtained was 46 kw, which is 50% higher than the maximum value possible with the 20 microsecond pulse. Due to the fact that the threshold power for arcing with this particular window was unusually low, the maximum equivalent transmitted power was only 23 Mw peak. However, the results indicate that considerably higher peak powers can be obtained with a short pulse.

4.7 Discussion Of Results

The results are summarized in Tables I and II. Windows coated by sputtering titanium monoxide in an argon atmosphere do not support multipactor, provided the coating is sufficiently thick. The thickness of sputtered coatings depends on the current, the cathode

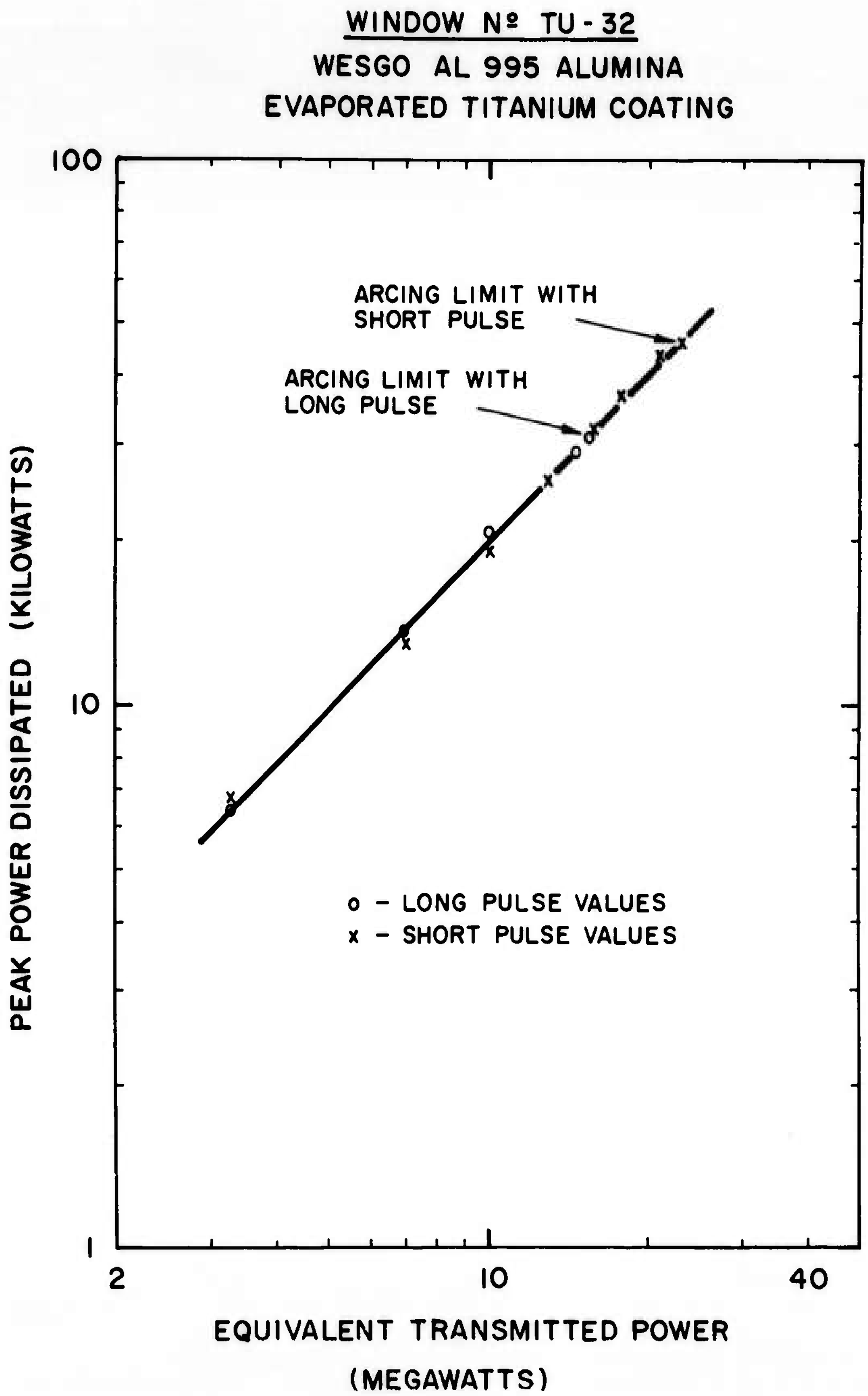

WINDOW Nº TU-32
WESGO AL 995 ALUMINA
EVAPORATED TITANIUM COATING
100
10
1
2
10
40
PEAK POWER DISSIPATED (KILOWATTS)
EQUIVALENT TRANSMITTED POWER
(MEGAWATTS)
ARCING LIMIT WITH
SHORT PULSE
ARCING LIMIT WITH
LONG PULSE
o - LONG PULSE VALUES
x - SHORT PULSE VALUES

Figure 14

potential, the molecular weight of the positive ion, and the duration of the operation. In the experiments described here, the potential was kept constant, thus coating thickness is related to the product of current and time. Coatings applied for 240 mA minutes at 1300 volts appear to be too thin to suppress multipactor, while coatings of 500 mA minutes and above greatly increase window losses. The optimum is about 400 mA minutes, but further tests will be needed to confirm these limits.

For sputtering in a mercury atmosphere, the optimum current-time product is less than for argon due to the heavier mercury ion. Coatings of 130 to 300 mA minutes are satisfactory. Thickness limits have not yet been determined. The rate of sputtering has considerable bearing on the degree of contamination of the coating. For a given pressure, contaminating gases would be expected to arrive at the substrate at a constant rate. High sputtering currents are

desirable, therefore, to reduce the contamination. A low sputtering current was used for the coating in TU 33. Although a thick coating was deposited, considerable clean up was necessary.

Evaporated titanium coatings with resistivities of 10^7 ohms per square and above need a clean-up operation to make them suitable for multipactor suppression. Attempts to avoid the necessity for this clean up by removing possible sources of contamination (such as heliarc welds) from the test unit and by careful processing, were not successful. Coating the cylindrical walls of the cavity in addition to the ceramic also failed to eliminate the necessity for clean up. Coatings with resistivities in the range 10^6 ohms per square were much more successful, few, if any, clean-up discharges being necessary.

TABLE I

SUMMARY OF HIGH POWER TESTS ON SPUTTERED TITANIUM MONOXIDE COATINGS

Test Unit	Window Ceramic	Cavity Q_L	Sputtering time and current	Peak Power Dissi-pated kW	Peak Power Approx. Trans-mitted Mw	Average Power Dissi-pated watts	Average Power Approx. Trans-mitted kW	Remarks
Argon Atmosphere								
21	Beryllia	1300	10mA,30 min 5mA,30 min	50	22	570	245	No multipactor throughout test.
24	Beryllia	1000	4mA,60 min	100	-	70	-	Severe multipactor.
26	Alumina	500	8mA,60 min	67	11	134	23	Low Q. No multipactor but some outgassing.
28	Beryllia	480	15mA,30 min 6mA,15 min	-	-	-	-	Low Q. Not tested at high power.
Mercury Atmosphere								
23	Beryllia	1200	1.5mA,90 min	42	17	510	200	No multipactor until crossed magnetic field applied.
25	Beryllia	1300	4mA,70 min	50	22	535	230	No visible multipactor. small pressure increase at high average power with magnetic field
33	Alumina	1350	1mA,300min	94	42	150	68	Intermittent multipactor initially.

T A B L E II

SUMMARY OF HIGH POWER TESTS ON EVAPORATED TITANIUM COATINGS

Test Unit	Window Ceramic	Coating resistivity ohms/sq.	Cavity Q_L	Peak Power: Dissipated kw	Peak Power: Approx. Transmitted Mw	Average Power: Dissipated watts	Average Power: Approx. transmitted kW	Remarks
20	Beryllia	$< 10^7$	1030	64	22	350	120	Both sides of window in vacuum, multipactor during initial operation.
22	Alumina	$< 10^7$	1500	45	22	230	115	Cavity walls coated. Multipactor during initial operation.
29	Beryllia	10^6	1300	55	24	750	320	No multipactor.
31	Beryllia	10^6	1300	90	40	650	280	Window from TU 29 tested after heat treatment. No multipactor. Peak power achieved with short pulse.
32	Alumina	10^7	1500	46	23	200	100	Slight multipactor during initial operation.

The application of a crossed magnetic field to a test unit operating at high power may induce multipactor which would otherwise not occur. This procedure is useful for testing borderline coatings which may be on the point of supporting multipactor. The best coatings are not affected by a magnetic field. A crossed magnetic field is also useful during the clean-up process for increasing the intensity of the discharges and shortening the duration of the operation.

It has not been possible to reach the peak powers achieved in Task B during the first year of the contract. Similar results cannot be expected, however, since the present window tests are carried out under different conditions. Ceramic discs tested during the Task B program were shrunk into copper cylinders which were then mounted directly into

the test facility without further processing. The windows were tested in a ring resonator using 3 microsecond pulses and average powers up to 50 Kw.

The present practice is to use windows which are metallized and brazed into water-cooled assemblies. These are then built into test units which are processed in the same way as an actual tube. Conditions are much closer, therefore, to those existing at practical windows. The units are tested in resonant cavities using 20 microsecond pulse widths at equivalent average powers up to 300 Kw, six times the maximum average power previously used.

The peak power limitation due to arcing within the cavity appears to be related to the pulse width. It is known that, in general, breakdown requires a certain length of time and that this time becomes shorter as the

electric intensity is increased. The evidence so far indicates that the peak power can be increased from 50 to 100% by reducing the pulse width from 20 to 3 microseconds. This would explain the difficulty that has been experienced in reaching high peak powers with a 20 microsecond pulse.

Since incorporating additional water cooling in the test units, higher average powers have been possible. The cooling is still not completely efficient, but no longer presents a limitation. Beryllia windows with evaporated coatings have dissipated average powers up to 750 watts (320 kW E.T.P.) without adverse effects either on the window or the coating. The limitation has been due to the peak power, which reached the arcing threshold even at the maximum rated duty of 2%. When testing alumina windows, the average power has been kept below 250 watts dissipation (about 125 kW E.T.P.) to avoid destruction of the window.

All of the evaporated coatings tested so far were applied after the window had been brazed into an assembly. In some applications it would be preferable to coat the window prior to the brazing operation. It was expected that a brazing cycle would not damage the coating if carried out in a reducing atmosphere, and this has been tentatively confirmed by experiment. The coating tested in TU 29 was subsequently heat-cycled in dry hydrogen to 750°C and retested in TU 31. A similar performance was obtained before and after heat treatment, multipactor being successfully suppressed.

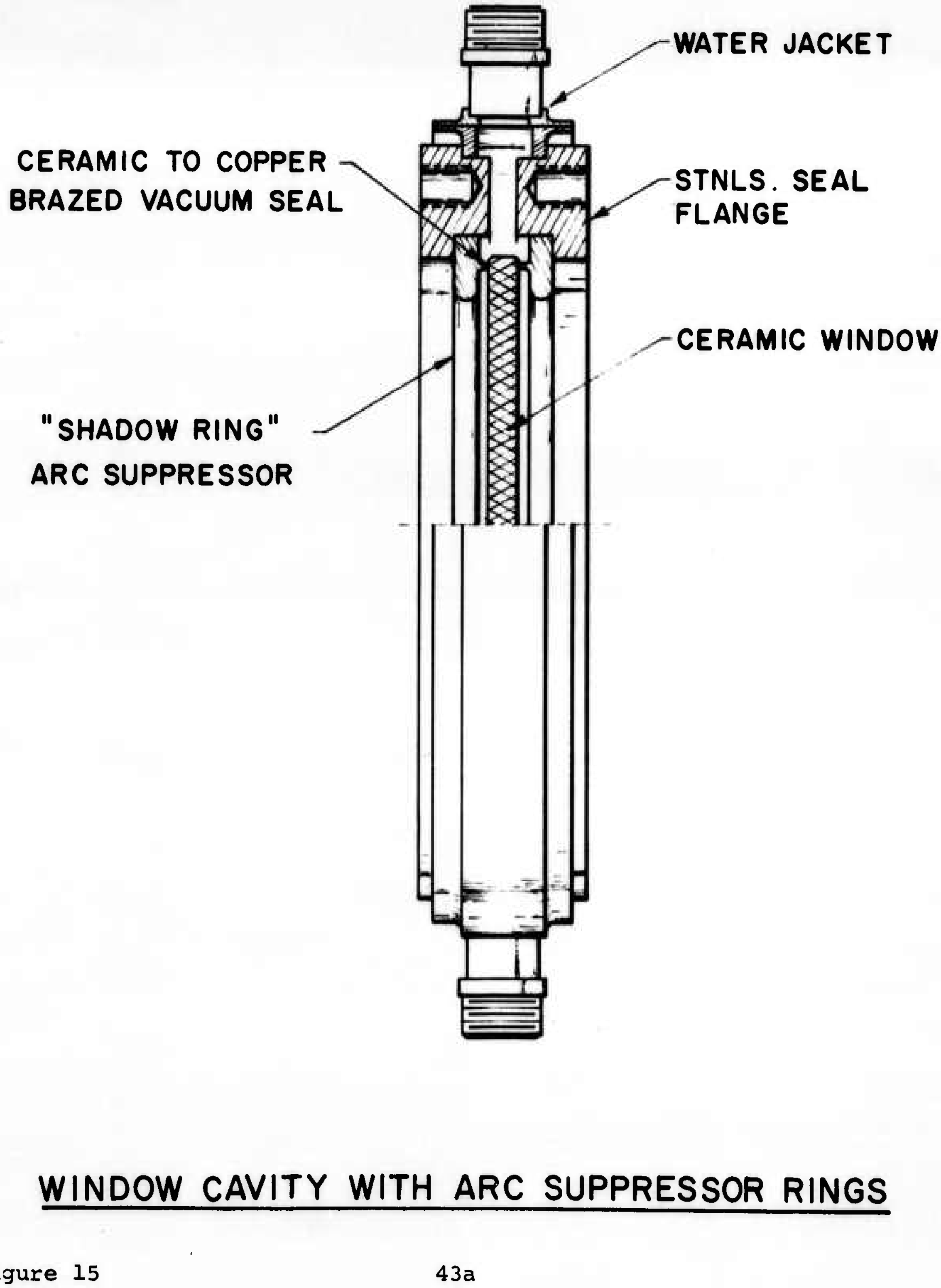
4.8 Arcing

The maximum peak power that can be dissipated in the window cavities is limited by arcing at the metal-dielectric junction. Arcing invariably occurs at the top and bottom of the cavity, corresponding to the regions of maximum electric intensity in the TE_{111} mode.

It is clear that if the peak power is to be increased substantially, the electric field at the metal-dielectric junction must be weakened, or alternatively the junction must be moved to a position of weaker electric field. Both approaches have been pursued during this quarter.

One attempt to weaken the electric field at the metal-dielectric junction was by the use of arc suppressor rings situated near the ceramic surface. A window design employing arc suppressor rings is shown in Fig. 15. The object of the rings is to divert electric field lines from the junction, thereby reducing the chance of arcing at this point.

Window assemblies built to this design have been tested in units pressurized on both sides of the ceramic. So far the results have been disappointing. Arcing at the

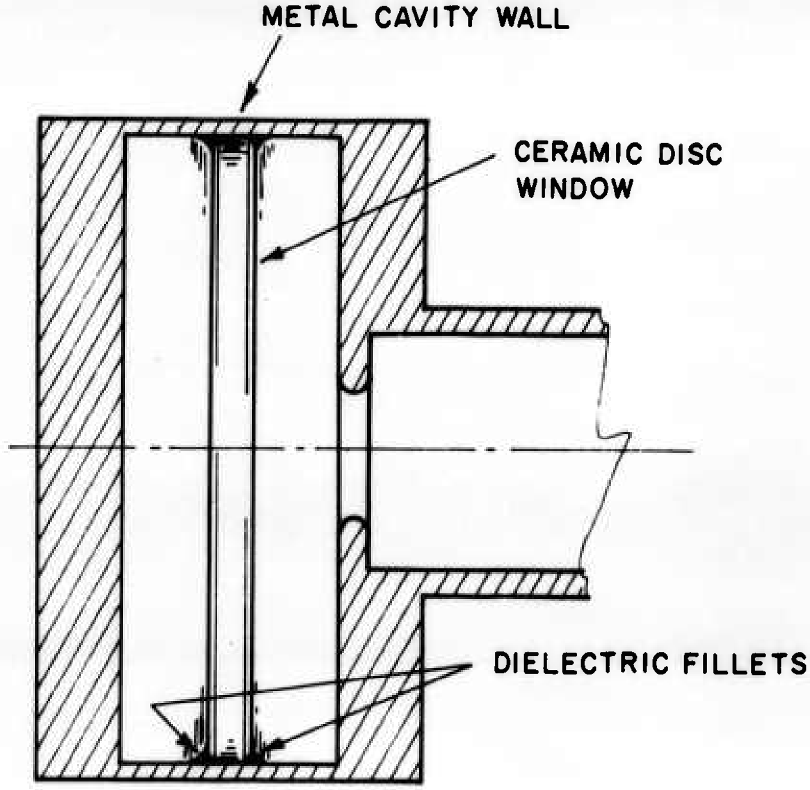


WINDOW CAVITY WITH ARC SUPPRESSOR RINGS

Figure 15

seal has occurred at comparatively low powers. The maximum peak power possible was 46 kw (23 Mw E.T.P.) which is no higher than the sparking threshold in units without rings. Since, in this design, the metal-ceramic braze was made on the face of the ceramic disc, it was difficult to confine the metalizing and arcing may have been promoted by the uneven edge. It is intended to investigate the field distribution in the region of the junction with field plots on resistance paper. A more satisfactory design should be possible with this additional information.

Another method of reducing the electric intensity is by means of dielectric fillets adjacent to the ceramic and metal cylinder. The arrangement is shown in Fig. 16. Due to the higher permittivity, the electric intensity has a lower value in the dielectric and the metal-dielectric junction is transferred



DIELECTRIC FILLETS AT CERAMIC-METAL JUNCTION IN RESONANT CAVITY

Figure 16

to a position of weaker field. The dielectric is applied to completed assemblies in the form of a viscous liquid and allowed to set. One problem is to find a suitable material; ideally it should have the following properties:

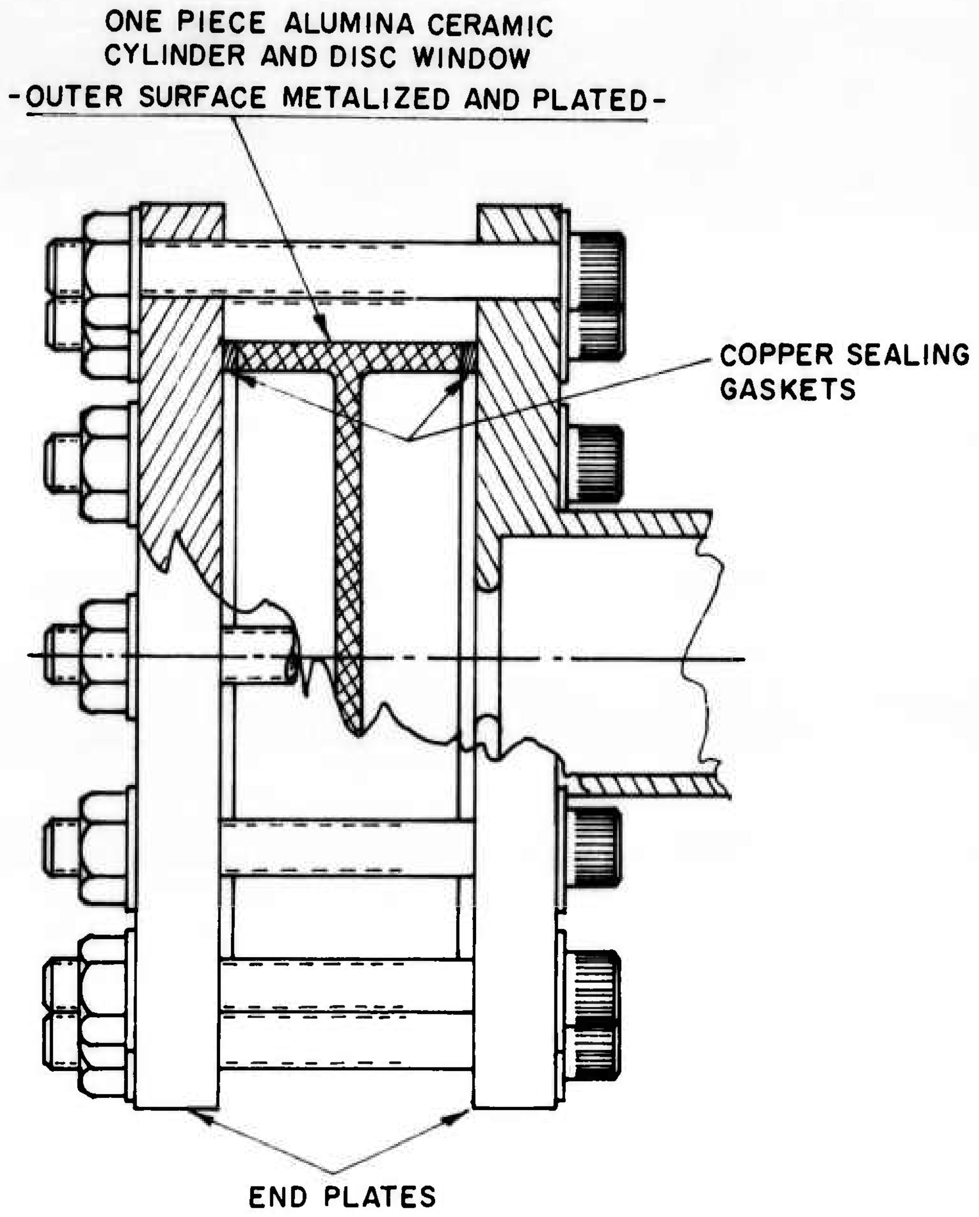
1. high dielectric strength
2. low loss at microwave frequencies
3. bond to metal and ceramic
4. low vapor pressure
5. be capable of withstanding temperatures up to 400°C

Most epoxy resins are unsuitable because of the temperature requirement. This means that units employing such materials can not be baked under vacuum. However, in order to test the principle, a window containing fillets of Araldite 502 was assemblied in a modified unit which could be pressurized with SF_6 gas on both sides of the ceramic.

When tested at high power, this unit dissipated powers up to 70 kw peak (35 MW E.T.P.), about 30% higher than the usual arcing limit. On dismantling the unit, it was noted that severe tracking had occurred in the Araldite. New fillets would be required, therefore, before the window could be used a second time. This fact, together with its inability to stand high temperature, limits the use of this material.

Fillets of a ceramic cement (Eccoceram) were tried, but these reduced the Q of the cavity, preventing high fields being obtained.

A resonant cavity design in which the metal-ceramic junction is placed in a region of weak electric field is shown in Fig. 17. A specially shaped ceramic is used which transfers the junction to the cavity end plates. The cylindrical wall of the cavity



FLANGED WINDOW ASSEMBLY

Figure 17

is formed by metallizing and plating the external surface of the ceramic. A ceramic of the required shape was fabricated from a disc and two cylinders of alumina. This was used for low power measurements to determine the correct dimensions for a cavity resonance near 2700 Mc/s. Having finalized the dimensions, a single ceramic member was made and this will be tested during the next quarter.

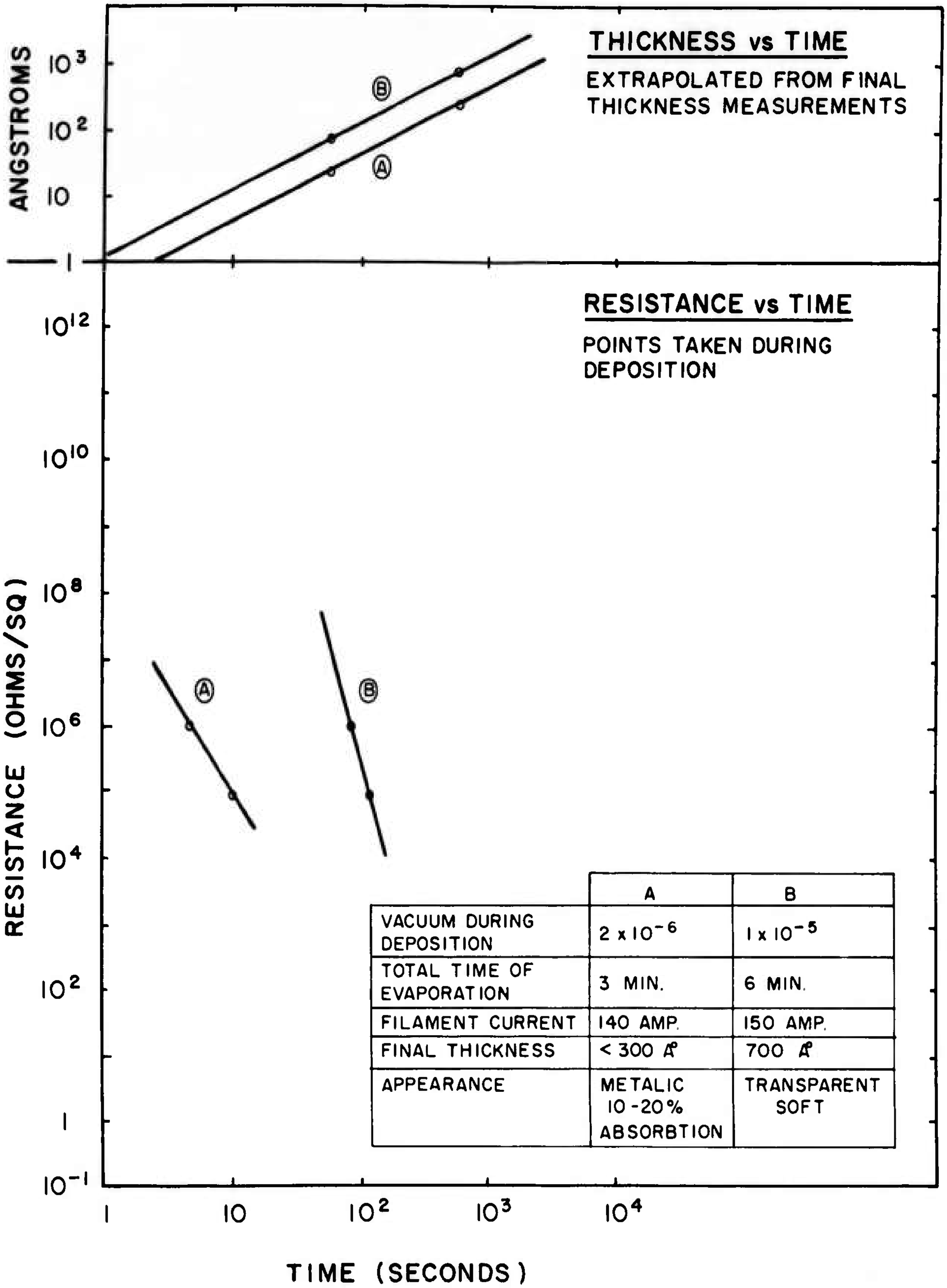
4.9 Thickness Measurements On Evaporated Titanium Films

Some experiments have been carried out using equipment at the University of California, involving the vacuum evaporation of titanium metal on glass substrates. The electrical resistance was continuously monitored during deposition, and the film thickness was measured at the end of deposition using a Reichert polarization interferometer. A G.R. megohmmeter and a transistor curve-tracing

oscilloscope was used for the resistance measurements. A shutter prevented deposition on the test plate until the filament temperature and the vacuum level stabilized. Often the vacuum could be improved an order of magnitude during this stabilization and depositions at pressures lower than 4×10^{-7} Torr were possible.

Results are shown in Figs. 18 and 19. Fig. 18 shows thickness versus time, assuming a linear relationship and the measured values of thickness at the end of the coating. Fig. 19 shows resistance versus time. Both figures show results for two different pressures in the bell jar.

Although the accuracy of the measurements was limited by the inability to measure films of less than 300 A° and by the difficulty in making very rapid resistance measurements, the curves are thought to be typical.



	A	B
VACUUM DURING DEPOSITION	2×10^{-6}	1×10^{-5}
TOTAL TIME OF EVAPORATION	3 MIN.	6 MIN.
FILAMENT CURRENT	140 AMP.	150 AMP.
FINAL THICKNESS	< 300 Å	700 Å
APPEARANCE	METALIC 10-20% ABSORBTION	TRANSPARENT SOFT

Figure 18

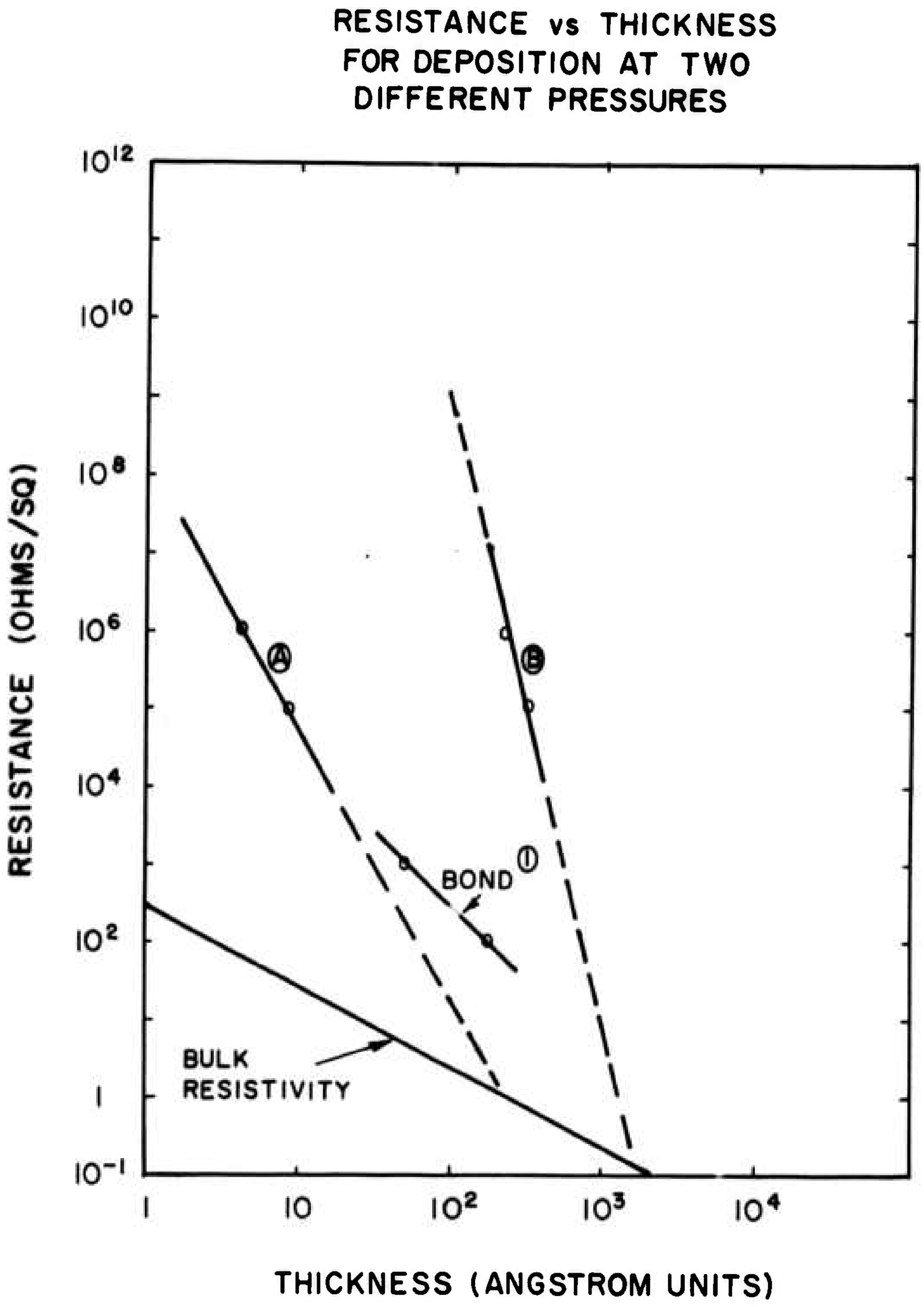

RESISTANCE vs THICKNESS
FOR DEPOSITION AT TWO
DIFFERENT PRESSURES
RESISTANCE (OHMS/SQ)
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
1
10^{-1}
A
B
BOND
1
BULK
RESISTIVITY
1
10
10^{2}
10^{3}
10^{4}
THICKNESS (ANGSTROM UNITS)

Figure 19

Data is also shown from Bond[1] in Fig. 19 for comparison. The results are, in general, in keeping with studies of the behavior of thin films which are discussed in the literature, but the values are more quantitative and specific to window coating work.

The composition of the films deposited under different vacuum conditions have been discussed by numbers of authors. It depends largely on collisions and reactions between atoms en route to the target, and reactions between arriving molecules at the target surface. Since the mean free path for air at 10^{-5} Torr is about 1000 cm, and the distance between the target and source in our experiments is only about 20 cm, the probability of collision en route is small. The arrival rate of gas atoms at the surface is large, however, at 10^{-5} Torr on the order of 1 mono molecular layer every .2 sec. At 100 A°/min.

1. W. L. Bond, Journal of the Optical Society of America, Vol. 44, No. 6, June 1954.

deposition rate, we have about the same arrival rate of titanium. Since titanium is an active metal, most of the gas molecules may be expected to be built into the deposited film, and this is what we seem to observe.

At 10^{-6} Torr, however, things are very much better, with one-tenth of the gas contamination arriving at the target.

The conclusions from these curves and from the appearance of the films are that both the optical and electric properties of titanium films evaporated at a rate of about 100 A^{o}/min. are greatly affected by changes in the vacuum environment during evaporation between 10^{-5} and 10^{-6} Torr. Higher rates of evaporation would be less affected, while a lower rate of deposition might be even more strongly affected, although the discussion above seems to indicate that the films may

already be saturated with dissolved gases under the present conditions of deposition. The work also suggests that for good control of the vacuum during coating, it is essential to avoid deposition on the target until the vacuum can recover from the filament outgassing which always occurs just before evaporation begins.

A third conclusion is that resistance measurements do provide an accurate method of controlling the thickness of films in the range of 10-100 A° if the evaporation can be stopped at a given resistance value, but only if the vacuum level during evaporation can be accurately controlled.

5. CONCLUSIONS

1. Approximate thickness limits for argon sputtered titanium monoxide coatings have been obtained, within which the useable range of coatings must lie. In terms of sputtering time and current

at a cathode potential of 1300 volts and a gas pressure of 1 micron, the lower limit is greater than 240 mA minutes and the upper limit less than 500 mA minutes. These values are tentative and will need to be confirmed.

2. For sputtering in a mercury atmosphere coatings applied for 130 to 300 mA minutes at 1300 volts and a pressure of 1 micron are satisfactory. Thickness limits have not yet been determined.

3. The clean-up process which occurs during the initial operation of some coated windows can be avoided by making the coatings sufficiently thick. The thinner the coating the more troublesome is the clean-up process.

4. While the peak power is still limited by arcing at the metal-dielectric seal, recent results have indicated that higher peak powers are possible with shorter pulse widths.

5. Beryllia windows with evaporated titanium coatings will operate satisfactorily up to average powers of at least 750 watts dissipation (320 kW equivalent transmitted power).

Coating resistivities at deposition between 1.10^6 and 1.10^7 ohms/square are satisfactory, in a vacuum of 10^{-5} Torr. Higher resistivities require a clean-up period. A low limit has not yet been found.

6. An evaporated titanium coating has been heat-cycled to 750°C in dry hydrogen without adverse effects.

7. Measurements on thickness and resistivity of evaporated films of titanium with pressure as a parameter have shown a well defined correlation between thickness and resistivity, and indicate the importance of good control of pressure during evaporation. From these measurements it is concluded that the evaporated film thicknesses so far found satisfactory for multipactor suppression are in the range of 100 - 300 Angstroms.

6. PROGRAM FOR THE NEXT INTERVAL

1. Work on sputtered titanium monoxide coatings using argon and mercury atmospheres will be continued. Thickness limits for argon coatings will be refined and satisfactory limits for mercury coatings established.

Measurements of coating resistivity of the sputtered coatings will be made similar to those for evaporated coatings.

2. Evaporated titanium coatings will be investigated further in order to establish satisfactory specifications of coatings, in particular an upper limit for thickness.

3. The relationship between maximum peak power and pulse width will be investigated.

4. Attempts to increase the peak power by suitable modifications to the metal-dielectric seal geometry to raise the arcing level will be continued.

5. Further investigations will be carried out on the effect of heat treating both evaporated and sputtered coatings.

6. An analysis of the gas evolved during a multipactor discharge will be carried out.

7. The evaluation of other types of window will be started with experiments on a domed-shaped window coated to prevent multipactor.

7. <u>IDENTIFICATION OF KEY PERSONNEL</u>

The hours worked by all those participating in the program are as follows:

	Manhours
D. Preist	85.0
B. Hill	146.0
J. Zegers	294.0
K. Scholz	185.0
I. Coutts	324.5
A. McConn	12.0
R. Hayes	412.0
B. Barnaby	45.0
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